

Forces on a Transverse Circular Cylinder In a Steady,
Uniform Flow near a Plane Boundary

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1975

AN ABSTRACT OF THE THESIS OF

BLAINE HAFEN for the degree Master of Ocean Engineering
(Name)

in Civil Engineering presented on 27 May 1975
(Major Department) (Date)

Title: FORCES ON A TRANSVERSE CIRCULAR CYLINDER IN A
STEADY, UNIFORM FLOW NEAR A PLANE BOUNDARY

Abstract approved: _____
Dr. John H. Nath

An experimental study was conducted to determine the hydrodynamic forces on smooth and roughened circular cylinders as influenced by a nearby plane boundary. The ambient flow was perpendicular to the cylinder and parallel to the boundary. Measurements were taken in a water channel and a wind tunnel to obtain the influence of the boundary on the Strouhal number, lift and drag forces, and wake configuration. Reynolds numbers in the wind tunnel varied from 2×10^4 to 8×10^4 , and the Reynolds number in the water channel was fixed at 5800. The value of C_D for a smooth cylinder was found to increase about 20% to 60% as the cylinder neared the boundary, but at the boundary C_D was about 15% less than the value in the free stream. Calculated values of C_D based on the Strouhal number measured in the water channel compared favorably with C_D values determined in the wind tunnel. The lift force was always positive due to wake effects.

Forces on a Transverse Circular Cylinder in a Steady,
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by

Blaine Hafen

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Ocean Engineering

June 1975

T167546

APPROVED:

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Date thesis is presented 20 May 1967

Typed by Opal Grossnicklaus for Blaine Hafen

ACKNOWLEDGEMENTS

This thesis was supported entirely by the National Oceanic and Atmospheric Administration under Sea Grant Contract 04-5-158-2 at Oregon State University. The writer would like to thank this institution for its support, and the United States Navy and their Post-graduate Program for making it possible to attend Oregon State University.

The writer also wishes to thank Drs. John H. Nath and Tokuo Yamamoto. Their advice and encouragement during the experimentation and preparation phases of this thesis have been greatly appreciated.

TABLE OF CONTENTS

	<u>Page</u>
1. 0 INTRODUCTION	1
2. 0 THEORETICAL AND REAL FLOW CONSIDERATIONS	4
2. 1 Flow About a Circular Cylinder Without Wake Formation	4
2. 11 Pressure Distribution on a Circular Cylinder	5
2. 12 Lift Forces Due to the Proximity of a Plane Boundary	6
2. 2 Fluid Flow About a Circular Cylinder with Wake Development	7
2. 21 Boundary Layer Separation	8
2. 22 Vortex Formation, Shedding Frequency, and Wake Size	10
2. 23 Drag Forces	12
2. 24 Lift Forces	14
3. 0 EXPERIMENTAL TECHNIQUE AND EQUIPMENT	16
3. 1 Wind Tunnel Force Measurements of a Circular Cylinder Near a Plane Boundary	16
3. 2 Water Channel Hydrogen Bubble Flow Visualization of the Flow Configuration Around a Circular Cylinder Near a Plane Boundary	20
4. 0 RESULTS	22
4. 1 Coefficient of Lift for a Smooth Cylinder	22
4. 2 Coefficient of Lift for Roughened Cylinders; $0.0165 < \epsilon/d < 0.0234$ and $0.0325 < \epsilon/d < 0.0468$	22
4. 3 Coefficient of Drag for a Smooth Cylinder	23
4. 4 Coefficient of Drag for Roughened Cylinders; $0.0165 < \epsilon/d < 0.0234$ and $0.0325 < \epsilon/d < 0.0468$	23
4. 5 Stagnation and Separation Points for a Smooth Cylinder	24
4. 6 Wake Width for a Smooth Cylinder	24
4. 7 Strouhal Number for a Smooth Cylinder	25

5.0	DISCUSSION OF RESULTS	26
5.1	Coefficient of Drag for a Smooth Cylinder	26
5.11	Influence of Wake Size on the Coefficient of Drag	27
5.12	Influence of Vortex Shedding Frequency on the Coefficient of Drag	28
5.2	Coefficient of Drag for Roughened Cylinders; 0.0165 < ϵ/d < 0.0234 and 0.0325 < ϵ/d < 0.0468	30
5.3	Coefficient of Lift for a Smooth Cylinder	30
5.31	Fluctuating Lift	31
5.32	Influence of Separation and Stagnation Points	32
5.4	Coefficient of Lift for Roughened Cylinders; 0.0165 < ϵ/d < 0.0234 and 0.0325 < ϵ/d < 0.0468	33
5.5	Boundary Layer Separation on the Plane Boundary	33
6.0	APPLICATION OF RESULTS	35
7.0	CONCLUSIONS	37
8.0	FIGURES	39
	LIST OF REFERENCES	77
APPENDIX	Tabular Results of Experimentation in the Wind Tunnel and Water Channel	80

ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1. Streamlines for Steady Two Dimensional Potential Flow.	40
2. Pressure Coefficient as a function of θ , (10).	40
3. Circular Cylinder Near a Plane Boundary, (27).	41
4. Distribution of Doublets for Uniform Flow Past Two Cylinders, (27).	41
5. Lift Coefficient for a Smooth Cylinder by Potential Flow Theory and Experimentation, (28).	42
6. Asymmetrical Wake Behind a Smooth Cylinder Near a Plane Boundary.	43
7. Strouhal Number as a Function of Reynolds Number for a Smooth Circular Cylinder, (20).	43
8. Splitter Plate Wake Interference Element, (21).	44
9. Drag Coefficient for Circular Cylinders as a Function of the Reynolds Number, (24).	45
10. Lift Coefficient for Smooth Circular Cylinders as a Function of e/d .	45
11. Plan View O. S. U. Low Velocity Wind Tunnel.	46
12. Velocity Profiles in Wind Tunnel at Right End of Test Section as Viewed from Upstream.	47
13. Velocity Profiles in Wind Tunnel at left End of Test Section as Viewed from Upstream.	47
14. Wind Tunnel Velocity Profiles at Centerline of Test Section.	48
15. Boundary Layer Velocity Profiles in Wind Tunnel (Average Values Taken Along Length of Test Section).	48

<u>Figure</u>		<u>Page</u>
16.	Elevation View of Test Cylinder in Wind Tunnel.	49
17.	Roughened Cylinder Mounted in Wind Tunnel with Calibration Pulley System.	50
18.	Strain Gage Attachment and Joint Between Test Section and Dummy Section.	50
19.	Strain Gage Measurement Flow Chart.	51
20.	Differential Pressure Measurement Flow Chart.	51
21.	Strain Gage Readings of F_L for Smooth and Roughened Cylinders in the Wind Tunnel.	52
22.	Strain Gage Readings of F_D for Smooth and Roughened Cylinders in the Wind Tunnel.	53
23.	Recirculating Water Channel Test Section.	54
24.	Recirculating Water Channel.	54
25.	Plan View of Recirculating Water Channel.	55
26.	Spatial Flow Profiles in Water Channel.	56
27.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.0625$.	57
28.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.125$.	57
29.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.25$.	58
30.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.375$.	58
31.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.50$.	59
32.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.75$.	59

<u>Figure</u>		<u>Page</u>
33.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.875$.	60
34.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.00$.	60
35.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.125$.	61
36.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.25$.	61
37.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.50$.	62
38.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.75$.	62
39.	Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 2.0$.	63
40.	Lift Force Coefficient for a Smooth Cylinder as a Function of e/d .	64
41.	Lift Force Coefficient for a Roughened Cylinder as a Function of e/d , $0.0165 < e/d < 0.0234$.	65
42.	Lift Force Coefficient for a Roughened Cylinder as a Function of e/d , $0.0325 < e/d < 0.0468$.	66
43.	Drag Force Coefficient for a Smooth Cylinder as a Function of e/d .	67
44.	Drag Force Coefficient for a Roughened Cylinder as a Function of e/d , $0.0165 < e/d < 0.0234$.	68
45.	Drag Force Coefficient for a Roughened Cylinder as a Function of e/d , $0.0325 < e/d < 0.0468$.	69
46.	Stagnation Point on a Smooth Cylinder as a Function of e/d , $Re = 5800$.	70

<u>Figure</u>		<u>Page</u>
47.	Upper and Lower Relative Separation Points on a Smooth Cylinder as a Function of e/d , $R_e = 5800$.	70
48.	Relative Wake Width for a Smooth Cylinder as a Function of e/d , $R_e = 5800$.	71
49.	Strouhal Number for a Smooth Cylinder as a Function of e/d , $R_e = 5800$.	71
50.	Comparison of Drag Force Coefficients for a Smooth Cylinder as a Function of e/d .	72
51.	Wake Width and Coefficient of Drag for a Smooth Cylinder as a Function of the Base Pressure Parameter, k , (23).	73
52.	Drag Force Coefficient on Circular Cylinders at Varying Surface Roughnesses, (24).	73
53.	Lift Force Coefficient on a Smooth Cylinder Immersed in the Boundary Layer as a Function of e/d ($e+d/\delta \approx 0.55$), (12).	74
54.	Maximum Values of the Coefficient of Lift as a Function of e/d .	75
55.	Maximum Values of the Coefficient of Drag as a Function of e/d .	76

NOTATIONS

A	Projected frontal area of body
C_D	Coefficient of drag
C_L	Coefficient of lift
F_D	Horizontal force per unit length of cylinder
F_L	Vertical force per unit length of cylinder
R_e	Reynolds number $R_e = \frac{Ud}{\nu}$
S	Strouhal number $S = \frac{fd}{U}$
S^*	Wake Strouhal number $S^* = \frac{fd'}{U_s}$
U_s	Velocity of free streamlines $U_s = kU$
a	Radius of cylinder
d	Diameter of cylinder
d'	Wake width between parallel free streamlines
e	Gap between cylinder and bottom boundary
f	Vortex shedding frequency
ϵ	Height of Cylinder Surface Roughness Elements
k	Base pressure parameter $k = U_s/U$
m	Strength of doublet
q_n	Doublet position and strength parameter
s	Distance from center of cylinder to bottom boundary
$\vec{v}$	Velocity vector
ρ	Mass density of fluid
ν	Kinematic viscosity of fluid

δ	Boundary layer thickness
θ	Angle from horizontal axis of cylinder
ψ	Stream Function
ϕ	Scalar Velocity Potential

FORCES ON A TRANSVERSE CIRCULAR CYLINDER IN A STEADY, UNIFORM FLOW NEAR A PLANE BOUNDARY

1.0 INTRODUCTION

The circular cylinder is a geometrical shape that is used extensively in fluid flows as structural members and fluid transport conduit. The design of these systems near the bottom in an ocean environment requires that they withstand the lift and drag forces from the ocean currents which are due to waves, density distribution, tides, and winds.

As shown in Ippen (11) some of the strongest currents are caused by storm surge which is a phenomena caused by high winds and regions of low pressure. These currents can be parallel to the shoreline, as during bathystrophic storm tide, or at various angles of incidence to the shoreline depending on the wind direction and the relative location of low and high pressure regions. Few measurements of the magnitude of the induced currents are available; however, Murray (19) did measure the seaward bottom current during hurricane Camille in 1969. He reported the maximum current was 1.6 meters per second which was 5% of the wind speed as measured from an anemometer mounted twelve meters above sea level.

Since many pipelines are being placed in areas around the world where storm surge is a problem, the forces due to the resulting currents need to be known to ensure an adequate design. The

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Since many pipelines are being placed in areas around the world where storm surge is a problem, the forces due to the resulting currents need to be known to ensure an adequate design. The

magnitude of the forces depends on such factors as:

1. Reynolds number of the flow
2. Proximity of the ocean bottom or free surface
3. Oscillatory nature of the flow
4. Orientation of the cylinder axis to the flow
5. Cylinder surface roughness
6. Bottom boundary roughness and boundary layer thickness
7. Fluid turbulence

The subject of vertical and horizontal forces on circular cylinders in steady flow located at or near the bottom has been investigated by many authors. Brown (5), Beattie and Brown (2), and Jones (12) provided measurements of the forces when a smooth cylinder was in contact with the bottom. Cornish (9), Wilson and Caldwell (6), and Tavalacci (27) provided some data of the magnitude of the coefficients of lift and drag for a smooth cylinder near the bottom. Yamamoto, Nath, and Slotta (28) have reported on the forces due to wave induced currents on smooth circular cylinders near a plane boundary. The lift and drag coefficient data reported by the investigators for a smooth cylinder as it approaches the bottom boundary exhibits considerable scatter. Some work by Jones (12) considers the cylinder surface roughness, and only in the work done by Tavalacci is an attempt made to visualize the change in the flow configuration around the cylinder due to the proximity of the bottom

boundary. This lack of consistent and comprehensive data is discussed in the report by Yamamoto, Nath, and Slotta.

It is the purpose of this thesis to add to the increasing amount of knowledge of the fluid forces on circular cylinders by determining the forces on a circular cylinder near a plane boundary, the axis of which is perpendicular to a steady, uniform flow. The effect of cylinder surface roughness is investigated, and the flow configuration around a smooth cylinder is determined by a hydrogen bubble flow visualization technique. No attempt is made to determine the influence of free stream turbulence, bottom roughness, or end effects on the forces.

2.0 THEORETICAL AND REAL FLOW CONSIDERATIONS

2.1 Flow About a Circular Cylinder Without Wake Formation

The absence of a wake formation in the fluid flow past a bluff body, such as a circular cylinder, implies the inability of the fluid to transmit shear stresses. The study of fluid dynamics involving a frictionless flow which is also incompressible and irrotational is the basis for the potential flow theory. The potential flow theory can be used in many real flow conditions where a wake is not present, such as in converging flows and oscillatory flows about an object, wherein the time between oscillations precludes the formation of a wake. In these cases the potential flow theory provides good results. In addition, in flow conditions where a wake is formed the potential flow theory provides a basis for the understanding of all aspects of the flow problem.

Mathematically, the conditions for potential flow are defined as:

$$\nabla \cdot \vec{v} = 0 \quad (\text{incompressible}) \quad 2.1-1$$

$$\nabla \times \vec{v} = 0 \quad (\text{irrotational}) \quad 2.1-2$$

Due to irrotationality, the velocity vector, $\vec{v}$, can be represented by the gradient of a scalar function, ϕ , and on substitution,

$$\nabla \cdot \nabla \phi = 0 \quad 2.1-3$$

$$\text{or} \quad \nabla^2 \phi = 0 \quad (\text{Laplace's Equation}) \quad 2.1-4$$

If conditions are such that the fluid motion is entirely two-dimensional, a stream function, ψ , will exist which also satisfies Laplace's equation and describes the velocity field. The combination of ϕ and ψ can be shown as a complex potential, $w = \phi + i\psi$, which greatly simplifies potential flow calculations. Knowing either ϕ or ψ , the other function can be obtained from the Cauchy-Riemann conditions.

When the complex potential of a flow is known, a circular cylinder can be introduced into the flow by augmenting the complex potential in accordance with Milne-Thompson's circle theorem. This augmented complex potential can then be coupled with the Theorem of Blasius to determine the horizontal and vertical forces on the cylinder due to the fluid velocity field.

2.11 Pressure Distribution on a Circular Cylinder

As discussed in references (10) and (18), potential flow theory predicts a zero drag force on a circular cylinder due to the symmetrical nature of the flow configuration. This is shown in Figure 1, and the resulting symmetrical pressure distribution is illustrated in Figure 2. Figure 2 shows that the experimental measurements of the pressure distribution around a circular cylinder deviate considerably from those predicted by potential flow theory, except in the region of the stagnation point. The potential flow solution to the

problem, therefore, does not lead to satisfactory or useful results.

2.12 Lift Forces Due to the Proximity of a Plane Boundary

Utilizing the circle theorem and the theorem of Blasius mentioned previously in section 2.1, the forces on a circular cylinder as it approaches a plane boundary can be determined. This approach is taken in references (27) and (28). Figures 3 and 4 help to explain the results, with the following analytical expressions found for the forces:

$$F_D = 0 \quad 2.12-1$$

$$F_L = -4 \pi \rho \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \frac{m_j m_k}{(2s - a(q_j + q_k))^3} \quad 2.12-2$$

$$q_0 = 0 \quad 2.12-3$$

$$\text{where } q_n = \frac{1}{(2s/a) - q_{n-1}} \quad n = k \text{ or } j$$

In this thesis the terminology "lift force" is used in reference to the forces on a cylinder which act perpendicularly to the ambient flow vector. They may be in either a positive or negative coordinate direction. A more universal format for the presentation of the lift forces utilizes a dimensionless coefficient of lift, such that:

$$C_L = \frac{F_L}{1/2 \rho AU^2} \quad 2.12-4$$

The lift coefficient for a circular cylinder near a plane boundary in potential flow is graphically presented in Figure 5 as a function of the gap between the cylinder and the plane boundary. Also shown in Figure 5 is the effect of real flow as determined by Tivolacci (27). Although a lift force is predicted by potential flow, there exists a discrepancy between theory and the experimental data for a steady, uniform flow except when the gap is equal to zero. Therefore, the utilization of the limiting assumption of an inviscid fluid erroneously predicts the lift and drag forces on a circular cylinder in a steady, uniform, viscous flow near a plane boundary.

2.2 Fluid Flow About a Circular Cylinder with Wake Development

In a real fluid flow the presence of viscosity causes the flow to separate from the cylinder resulting in a wake behind the cylinder, the width of which increases as the distance from the cylinder increases. The velocity within the wake is less than the free stream velocity. This reduction in velocity is the result of lost momentum which is due to the drag on the cylinder. The size of the wake, and the resulting drag, is dependent on such factors as free stream turbulence, boundary layer development on the cylinder, submergence in the boundary layer of a nearby boundary, end effects (spiral vortices) and the Reynolds number of the flow. Besides these

factors, lift is influenced by the net circulation around the cylinder.

2. 21 Boundary Layer Separation

Because of viscosity a boundary layer is developed on the surface of a cylinder. In this boundary layer the fluid velocity is zero at the surface and nearly equal to the free stream velocity at a large distance from the surface. As the fluid flows around the circular cylinder the fluid accelerates from points A to B and A to D in Figure 1, and decelerates from B to C and D to C. As a result the pressure gradient is first negative from A to B or D and positive from B or D to C. Since the velocity in the boundary layer is less than the free stream velocity, the fluid momentum in the boundary layer is not great enough to overcome the presence of the adverse (positive) pressure gradient in the flow from points B or D to C; therefore, the fluid is brought to rest at some point in the boundary layer. A back flow occurs, and the flow separates from the cylinder. Classically, as presented in references (10), (24), and (7) the point of separation is defined as the point where the velocity gradient normal to the cylinder surface vanishes, that is:

$$\left. \frac{\partial u}{\partial y} \right|_{y=0} = 0 \quad 2. 21 - 1$$

where u = fluid velocity parallel to the cylinder surface

y = axis perpendicular to the cylinder surface

The point of separation on a circular cylinder in the free stream is influenced by the shedding of the alternating vortices from the top and bottom of the cylinder. This alternate shedding causes the point of separation to oscillate at the shedding frequency. It has been found experimentally, as shown in references (10) and (24), that separation occurs at approximately 82° from the front stagnation point for Reynolds numbers sufficiently low to ensure that the flow in the boundary layer up to the point of separation is laminar. At higher Reynolds numbers the boundary layer becomes turbulent, and the angle at which separation occurs, increases.

As shown in Figure 6, this separation gives rise to the development of a wake behind the cylinder whose configuration is dependent on Reynolds number, which is defined as:

$$R_e = \frac{Ud}{\nu} \quad 2.21-2$$

When the Reynolds number of the flow increases from zero, the point of separation moves from the rear stagnation point to a point approximately 82° from the front stagnation point with a resultant increase in wake dimension. As the Reynolds number increases past 10^5 the boundary layer goes through a transition from laminar to turbulent, gaining momentum in the process, which moves the point of separation toward the rear stagnation point, causing a decrease in wake size.

The lower separation point on the cylinder, as denoted in Figure 6, may be located at a greater angle from the front stagnation point than the upper separation point due to the influence of a nearby boundary, thereby affecting the size of the wake and the resulting horizontal and vertical forces on the cylinder.

2.22 Vortex Formation, Shedding Frequency and Wake Size

The formation of vortices in the wake of a circular cylinder in a uniform, steady flow has been theoretically presented by Von Kármán as the vortex street formed by their alternate shedding with a definite periodicity, dependent on the Reynolds number of the flow. Extensive experimental work has been done by Roshko (20, 21), Birkhoff (3,4), Chen (8), Kovasznay (14), Kronauer (15), and others to explain the mechanism of the formation of the periodic wake. Much of the existing work has been summarized by Marris in reference (17) but a complete understanding of the mechanism has not been achieved.

The dependence of the periodicity in the wake on the Reynolds number of the flow can be illustrated through the use of the Strouhal number,

$$S = \frac{fd}{U} \quad 2.22-1$$

The Strouhal number as a function of Reynolds number is shown in Figure 7. It is evident that over the range $Re = 4 \times 10^2$ to $Re = 2 \times 10^5$

the vortex shedding is regular and the Strouhal number is equal to approximately 0.21. It has been shown by Roshko (20) and Kovasznay (14) that the periodic wake appears at $R_e = 40$; the wake is stable and regular up to $R_e = 150$; between $R_e = 150$ and $R_e = 300$ the vortices gain energy and begin to interact, and above $R_e = 300$ an irregular wake exists.

The wake is defined by the vortex layers which originate from the separation points. These vortex layers are the continuance of the separated boundary layer which is well defined at first, but quickly becomes the familiar periodic wake structure known as the Von Kármán vortex street.

The influence of a nearby plane boundary on the mechanism of vortex shedding has not been thoroughly investigated; however, the work done by Roshko (21, 22) with a splitter plate located behind a circular cylinder, gives some insight into the possible effect of a nearby boundary. Roshko found that when a splitter plate 1.14 diameters long was in contact with the cylinder, the two parallel vortex rows in the wake were shielded from each other, and a vortex street was not developed. As the plate moved downstream away from the cylinder, the frequency of shedding decreased, as shown in Figure 8. He also noted that as the frequency decreased the distance between the vortex layers increased.

Although a plane boundary is a different type of wake

interference element, it is reasonable to assume that an interrelationship will exist between the frequency of vortex shedding, the wake size, and the nearness of the plane boundary.

2. 23 Drag Forces

As a consequence of the formation of a wake behind a cylinder, the velocities in a region behind the cylinder are less than those in the free stream. As shown in references (10) and (24), the momentum equation for a control volume encompassing the cylinder defines the sum of all forces acting on the control volume as equal to the change of the momentum flux into and out of the control volume. Due to the lower velocities in the wake there is a net momentum loss which is due to the drag force on the cylinder. The momentum loss can be related to the pressure around the cylinder, in that the pressure must be lower behind the cylinder than on the upstream face in order to create the drag force. This momentum loss, therefore, explains the pressure differences noted in Figure 2 between the potential flow theory and the measured pressures around a cylinder in a steady, uniform flow. This drag force is normally presented by a dimensionless coefficient of drag, such that:

$$C_D = \frac{F_D}{1/2 \rho A U^2} \quad 2. 23-1$$

A summary of experimental measurements of C_D as a function of

Reynolds number for cylinders in the free stream are shown in Figure 9 which does not show the data scatter.

Some effects on the wake and drag on a cylinder in the proximity of confining walls are given in reference (26). It was shown that as the ratio of the diameter of the cylinder to the width of the channel increased, the Reynolds number at which the onset of a periodic wake occurred, increased. A ratio of 1:5 gave an 18% increase in the measured drag on the cylinder.

Measurements of C_D for a cylinder in contact with the plane boundary are given in references (5) and (2). Considerable scatter was exhibited in the data from Beattie and Brown (2) which they concluded was most probably due to free stream turbulence; however, they did note a trend of C_D for subcritical Reynolds numbers to be lower for a cylinder in contact with the plane boundary than for a cylinder in the free stream. Brown (5) determined that C_D varied from 0.90 to 0.55 for Reynolds numbers of 0.6×10^5 and 3×10^5 respectively. Neither reference indicated the height of the bottom boundary layer in relation to the cylinder diameter nor included a velocity profile to indicate the uniformity of the flow.

The forces on a bluff body as it approaches a plane boundary were measured in references (9) and (6). Cornish (9) plotted C_D as a function of the relative height of a car model above the plane boundary, e/d . He found that C_D decreased for the range of e/d

from 0.6 to 0.0. Wilson and Caldwell (6), also noted that for Reynolds numbers of 33, 200 and 56, 600 the coefficient of drag decreased about 15% from the free stream value for e/d values less than unity. These findings correlate with those of references (5) and (2) for a cylinder in contact with a plane boundary. They indicate the drag force is quite sensitive to the proximity of a plane boundary, and that the drag decreases as the gap between the cylinder and the plane boundary decreases.

2.24 Lift Forces

The vortex formation in the wake of a cylinder not only affects the drag, but gives rise to a fluctuating lift force, as noted in reference (28). This fluctuating lift is primarily the result of the movement of the points of separation as the alternating vortices are shed from the cylinder. The action is such that as a vortex is shed from the top of the cylinder the upper separation point is pulled back along the cylinder and the lower separation point moves forward. A reverse movement occurs as a vortex is shed from the bottom of the cylinder. The effect is an instantaneous periodic pressure differential which causes a fluctuating lift force. The time averaged effect of this process results in a zero lift.

As discussed in section 2.12, there is a net vertical force on a cylinder as it approaches a plane boundary. In real flow it has

been shown that the front stagnation point is affected by the presence of the plane boundary, causing it to rotate in the direction of the plane boundary (27). It was also noted in reference (27) that the proximity of the plane boundary caused the lower separation point, as measured from the front stagnation point, to move back along the cylinder. This results in an asymmetrical wake, shown in Figure 6, which is larger on the upper portion of the cylinder. The effect is a low pressure region on the upper portion of the cylinder giving a net upward lift. The lift due to stagnation and separation point movement is shown in Figure 10 as that found experimentally by Wilson and Caldwell (6), Tivolacci (27), and reported by Ippen (11). All the existing experimental work leads to the conclusion that, contrary to potential flow theory, the lift force experienced by a circular cylinder in a uniform, steady flow is positive, that is away from the plane boundary.

3.0 EXPERIMENTAL TECHNIQUE AND EQUIPMENT

The lift and drag on a circular cylinder are affected by free stream turbulence, boundary layer on the cylinder, boundary layer of a nearby plane boundary, and spiral vortices generated at the ends of the test cylinder. Experimental work conducted in a low velocity wind tunnel and water channel was intended to perform the following:

1. Further validate the influence of the parameter e/d on the vertical and horizontal forces on a cylinder.
2. Determine the influence of surface roughness for various values of e/d .
3. Visualize the flow configuration around and the wake behind a cylinder in uniform, steady flow.

Free stream turbulence, bottom boundary layer, and end effects were not variable parameters, and it was attempted to limit their influence.

3.1 Wind Tunnel Force Measurements of a Circular Cylinder Near a Plane Boundary

Force measurements on a circular cylinder as it approaches a plane boundary were conducted in the low velocity, recirculating wind tunnel at Oregon State University, shown schematically in Figure 11. The test section of the tunnel is 1.52 meters wide, 1.22 meters high, and 9.14 meters long. Turning vanes are located at

all four corners, and a honeycomb flow straightener with 6.35 millimeter openings is located immediately upstream of the test section. Velocities in the wind tunnel can be adjusted through a control panel to vary between 3.67 and 13.72 meters per second with a fluctuation of approximately 1.5% about the mean velocity. These velocities are well below the criteria reported by Ball (1), and the flow can be considered incompressible.

Vertical velocity profiles of the flow were taken at three positions at the location of the test cylinder without the cylinder being present. These profiles are shown in Figures 12, 13, and 14. The velocity is seen to be nearly uniform within the range of heights above the plane boundary to be investigated, as qualified below. The boundary layer thickness at these velocities (δ defined where the velocity in the boundary layer equals 99% of the free stream velocity) was approximately 2 centimeters, as shown in Figure 15.

The spatial root mean square velocity variation due to the boundary layer was only significant when the gap between the bottom of the wind tunnel and the cylinder was 1.27 and 0.635 centimeters. In these two cases the maximum variation was 3% at 3.68 meters per second, 1% at 6.06 meters per second, and 2% at 9.35 meters per second. This variation is within the fluctuation about the mean velocity due to free stream turbulence; therefore, it was concluded that the effect of the boundary layer was small and could be ignored.

The test cylinder was a 10.16 centimeter diameter plexiglas tubing with 45.72 centimeter long dummy sections at either end which were rigidly connected to the floor and undercarriage as depicted in Figures 16 and 17. Measurements were made for one smooth and two roughened cylinders. The roughness obtained was $0.0165 < \epsilon/d < 0.0234$ for one cylinder and $0.0325 < \epsilon/d < 0.0468$ for the other. The cylinders were rigidly attached to a 19.05 centimeter aluminum bar, see Figure 18, which was machined as shown in Figure 16. Four strain gages were attached at each indicated location on the bar to form four external resistance arms for the Textronics type 3C66 carrier amplifiers. Figure 18 shows the attachment of two of the strain gages and the joint between the dummy and test sections. Strains on the force dynamometers were recorded as indicated schematically in Figure 19.

Prior to each run the test cylinder was calibrated with a system of weights and pulleys, shown in Figure 17, which was sensitive to 1 gram, to obtain a force-displacement record on the 2-channel recorder for both the horizontal and vertical directions. Recorded strains could then be reduced directly to forces. Once the equipment was calibrated for the height setting of the cylinder, the wind tunnel air velocity was adjusted to velocities of approximately 3.67, 6.10, 9.14, and 12.20 meters per second; internal wind tunnel air temperature was recorded; velocity measurements were recorded as shown

schematically in Figure 20, and strains were recorded in both the horizontal and vertical directions. Strain measurements were corrected for an experimentally determined linear drift which was due to the differential cooling of the aluminum bar when the wind tunnel was activated. This arrangement and sequence of events was utilized for the smooth and roughened cylinders for e/d values ranging from 0.0625 to 2.0.

In order to make the force dynamometer sensitive to small forces, the aluminum bar was machined to a thickness of 2.54 millimeters at the point of application of the strain gages. This resulted in a natural frequency of 28.5 cycles per second for the system. Based on a Strouhal number of 0.21, a velocity of 13.8 meters per second results in a vortex shedding frequency of 28.5 cycles per second, and a resonant condition would exist. Experimental velocities ranged from about 4.0 meters per second to about 13.0 meters per second. Large vibrations of the system were noticeable on the lift force recordings at the upper test velocity; therefore, a velocity of about 10 meters per second was the limiting velocity for the lift force measurements. Sample recordings of the lift force measurements at three test velocities are shown in Figure 21. Some vibration was evident in all the recordings, and a peak to peak average reading was used as the net lift force. This averaging was also used to obtain the drag force from the recordings. Sample drag

force recordings are shown in Figure 22.

3.2 Water Channel Hydrogen Bubble Flow Visualization of the Flow Configuration Around a Circular Cylinder Near a Plane Boundary

The recirculating water channel used is shown in Figures 23 and 24 and schematically in Figure 25. The channel is 2.44 meters long, 10.16 centimeters wide, and 61.0 centimeters high. The channel sides are made of 12.7 millimeter plexiglas. Two honeycomb flow straighteners with 1.5 millimeter openings were used to obtain a uniform flow.

A hydrogen bubble technique, such as that described in references (16) and (25), was used to visualize the flow around a 5.1 centimeter diameter smooth cylinder, and to determine the flow velocity. A 0.0762 millimeter copper wire was crimped by passing it through two inter-meshing gears, and then mounted vertically through the floor of the channel in the location shown in Figure 25. A 50 volt direct current, 1 ampere source was used to generate the hydrogen bubbles which were essentially streamlines, clearly showing the flow configuration around the cylinder.

The hydrogen bubbles were backlighted for photography, as shown in Figure 25, and movie pictures at 18 frames per second were taken of the flow as the source voltage was pulsed manually. Velocity measurements of the flow were taken from these pictures

as were the profiles shown in Figure 26. Figure 26 represents the spatial fluctuations in the velocity field observed in one frame of the movie pictures. Each profile represents a discrete line of bubbles, and not the same line observed with respect to time. A mean velocity of 0.12 meters per second was established with a deviation in the vertical velocity profile with respect to distance downstream as shown in Figure 26. This velocity resulted in a boundary layer at the cylinder of approximately 2 millimeters and a bubble rise to distance traveled ratio of about 1:20. No turbulence was visually observed through the action of the hydrogen bubbles, and as viewed from above, the plane of bubbles was contained within a 2 centimeter wide space.

Once the velocity was established, still pictures were taken of the flow at each position of the cylinder for e/d values of 0.0625 to 2.0. Five pictures were taken at each position with a time lag of 2.2 seconds between succeeding pictures. In this manner the vortices behind the cylinder were visualized at different phases of shedding. Typical flow configuration patterns for each position of the cylinder are shown in Figures 27 through 39. Movie pictures were taken of the flow around the cylinder, and again without the cylinder at the conclusion of the experiment to reconfirm the flow velocity. Differential pressure readings of the flow showed no variance in the velocity over the time interval of the experiment.

4.0 RESULTS

4.1 Coefficient of Lift for a Smooth Cylinder

The coefficient of lift as a function of e/d for a smooth cylinder is shown in Figure 40 for varying Reynolds numbers. The coefficient of lift is seen to be quite sensitive to the proximity of the plane boundary. The coefficient of lift is observed to decrease quite rapidly for e/d values of 0.0625 to 0.75, suddenly increase for $0.75 < e/d < 1.25$, peak at an e/d of about 1.125, and decrease to zero at an e/d of 1.75. The coefficient of lift decreases for a corresponding increase in Reynolds number for all values of e/d .

4.2 Coefficient of Lift for Roughened Cylinders; $0.0165 < \epsilon/d < 0.234$ and $0.0325 < \epsilon/d < 0.0468$

The lift coefficients for the roughened cylinders are shown in Figures 41 and 42. They have the same general shape as that for a smooth cylinder, except that instead of the sudden increase in C_L for a smooth cylinder at $0.75 < e/d < 1.25$, C_L decreases to zero at an e/d of 0.75 and 1.0 for the roughnesses $0.0165 < \epsilon/d < 0.234$ and $0.0325 < \epsilon/d < 0.0468$ respectively. The coefficient of lift decreases for a corresponding increase in Reynolds number for all e/d values.

4.3 Coefficient of Drag for a Smooth Cylinder

The coefficient of drag as a function of e/d for a smooth cylinder is shown in Figure 43. The coefficient of drag increases for all Reynolds numbers studied at an e/d value of 1.25, peaks at an e/d of about 0.875, and decreases steadily for $0.0625 < e/d < 0.875$. This increase in C_D ranges from 20% to 60% of the free stream value depending on the Reynolds number. The general trend to be observed for all Reynolds numbers investigated is that as the cylinder approaches the plane boundary the drag increases and has a peak value in the range $0.625 < e/d < 1.25$. The drag decreases for an e/d of 0.875 to 0.0625. A net decrease in C_D of about 15% from the value in the free stream is observed for the cylinder at an e/d of 0.0625. The strain gage force dynamometer system precluded a determination of C_D when the cylinder was in contact with the boundary since the friction between the cylinder and the boundary would bias any strain on the system due to drag forces.

4.4 Coefficient of Drag for Roughened Cylinders; $0.0165 < \epsilon/d < 0.0234$ and $0.0325 < \epsilon/d < 0.0468$

Figures 44 and 45 depict the change in the coefficient of drag for cylinder surfaces with relative roughnesses of $0.0165 < \epsilon/d < 0.0234$ and $0.0325 < \epsilon/d < 0.0468$ respectively. The coefficient of drag in Figure 44 still shows a slight increasing-decreasing trend,

but in Figure 45 the cylinder roughness causes the coefficient of drag to be relatively independent of e/d .

4.5 Stagnation and Separation Points for a Smooth Cylinder

The stagnation point for a cylinder near a plane boundary is below that for a cylinder in the free stream. The stagnation point as a function of e/d , shown in Figure 46, varies smoothly from -14° at an e/d of 0.0625 to 0° at an e/d of 1.5.

The relative separation points plotted in Figure 47 are the points where the streamlines visualized by the hydrogen bubbles deviate from the cylinder curvature and form the vortex layers. These points are located upstream of the actual separation points; however, their movement correlates directly with the movement of the actual separation points. Figure 47 shows that the angle at which the lower separation occurs decreases and that for the upper separation increases as e/d increases. It is noted that for the range $0.75 < e/d < 1.25$ the angle at which upper separation occurs decreases and then increases subsequently.

4.6 Wake Width for a Smooth Cylinder

The wake width, d' , is a measure of the distance between the vortex layers behind the cylinder where the vortex layers become parallel. The values plotted in Figure 48 are the average values

of the five still pictures taken at each e/d value. The measured d' is a relative width which is slightly larger than the actual wake width since the vortex layers visualized do not generate from the actual separation points as discussed in section 4.5. Figure 48 shows that d' decreases as e/d increases to about $e/d = 0.5$. It then increases slightly to an e/d of about 0.875, and remains fairly constant for $e/d > 0.875$.

4.7 Strouhal Number for a Smooth Cylinder

The movie pictures taken of the flow at all values of e/d were viewed frame by frame to determine the elapsed time between each successive vortex shedding. With the determination of shedding frequency the Strouhal number was calculated and is shown in Figure 49 as a function of e/d . It is seen that the Strouhal number increases from $e/d = 0.25$ to $e/d = 0.875$, decreases from an $e/d = 0.875$ to $e/d = 1.75$, and remains at a value of approximately 0.22 for e/d values of 1.75 and 2.0. For e/d values of 0.0625 and 0.125 a vortex layer was visible as seen in Figures 27 and 28; however, a periodic wake did not exist.

5.0 DISCUSSION OF RESULTS

5.1 Coefficient of Drag for a Smooth Cylinder

As shown in Figure 9, the expected value of C_D for a cylinder in the free stream, whose axis is perpendicular to the flow, for Reynolds numbers between 10^4 and 10^5 is approximately 1.2. The average value of C_D in Figure 43 at e/d values of 1.75 and 2.0 is 0.9. At these values of e/d the influence of the plane boundary is essentially negligible, and a C_D of about 1.2 should exist. As discussed in section 3.1, the bottom boundary layer is 2 centimeters thick and did not influence the drag force at a height of 17 centimeters or about $e/d = 1.75$. There is no measurement of the effect of the spiral vortices generated at the end of the test section, and it is assumed that their influence is small; however, a measureable free stream turbulence did exist as presented in section 3.1 as a fluctuation of 1.5% about the mean wind velocity. This free stream turbulence induces the cylinder boundary layer to become turbulent at lower Reynolds numbers than for a true steady flow. As presented by Ko and Graf (13), the turbulence intensity is a predominant factor in the variation of C_D , and a free stream turbulence of 1.5% is found to result in a decrease in the value of C_D from that in laminar flow. Therefore, it can be concluded that free stream turbulence did influence the experimental results. Since the fluctuation about the mean

free stream velocity is about 1.5% for the full range of e/d values, the predominant parameter influencing the character of the C_D curves is e/d . Values of C_D for this work are compared in Figure 50 with that reported by Tavalacci (27), and Wilson and Caldwell (6), and a fairly good correlation exists.

5.11 Influence of Wake Size on the Coefficient of Drag

As noted by Roshko (22), for a given cylinder the coefficient of drag increases in the range $10^3 < R_e < 10^5$ as the wake size decreases; however, for bluff bodies with the same projected frontal area the bluffer body will have a larger wake and a larger coefficient of drag. The inverse relation between drag and wake width for a given cylinder can be explained by looking at the interaction between the wake size and the points of separation. As the wake size increases the points of separation move forward toward the front stagnation point, and conversely, as the wake size decreases the points of separation move back away from the front stagnation point. When the separation point is forward (a large wake) the velocity in a stream tube at the point of separation will be higher than the free stream; however, it will be lower than the velocity for a stream tube when the point of separation is farther back (a small wake). The absolute value of the base pressure will therefore be higher for a small wake than for a large wake, and C_D will be higher for a small wake than for a large wake.

Figure 48 shows the variation in the wake size, d'/d , as a function of e/d . The wake size increases rapidly from $e/d = 0.5$ to $e/d = 0.0625$ indicating a decrease in the coefficient of drag, which is apparent in Figure 43. There is no large decrease in the wake size for $0.815 < e/d < 1.25$ to explain the peak in C_D of Figure 43; however, the minimum value of d'/d is lower than the value of d'/d at an e/d of 2.0, where the effect of the plane boundary is no longer present, indicating that the value of C_D should increase from that in the free stream. This increase is noted in Figure 43.

5.12 Influence of Vortex Shedding Frequency on the Coefficient of Drag

Roshko (21, 22), noted that for a wake interference element an increasing vortex shedding frequency corresponded to an increasing C_D . Figure 49 shows a decreasing frequency for an e/d less than 0.875; however, from e/d equal to 1.5 to 0.875 the frequency of shedding increases. The range of increasing and then decreasing shedding frequencies corresponds to the range of e/d values where C_D in Figure 43 increases and then decreases. The increase in C_D for the range $0.625 < e/d < 1.25$ was not noted by Wilson and Caldwell, but Figure 50 shows that the work done by Tavolacci indicates that an increase in C_D at an e/d of about 1.25 does occur. The decrease in C_D below an e/d of 0.875 corresponds to the decreasing shedding frequency in this range.

In reference (23) Roshko presents a free streamline method for determining C_D . This method modifies the method of Helmholtz-Kirchhoff by allowing the value of the free streamline velocity to vary, such that:

$$U_s = kU \quad 5.12-1$$

where k = base pressure parameter, greater than 1.0.

Although the two free streamlines leaving a cylinder which is near a plane boundary do not have the same velocity, which is a necessary condition when using the free streamline theory, the method presented by Roshko is used to observe if a correlation exists between the values of C_D found experimentally and those computed by the free streamline theory using the Strouhal numbers shown in Figure 49.

Roshko noted in reference (22) that,

$$k(d/d') = S/S^* \approx S/0.16 \quad 5.12-2$$

where S^* is a dimensionless wake Strouhal number defined as:

$$S^* = \frac{fd'}{U_s} \quad 5.12-3$$

Equation 5.12-2 is utilized in conjunction with the Strouhal numbers given in Figure 49 to obtain an expression for $k(d/d')$ at each value of e/d . The expressions for $k(d/d')$ are used with Figure 51 to obtain values of C_D for each value of e/d . This relation is plotted in Figure 50, and a good agreement with experimental results exists.

Although the free streamline theory is used rather loosely in this case, it does show that the values of C_D and the Strouhal numbers found experimentally do correlate.

5.2 Coefficient of Drag for Roughened Cylinders; $0.0165 < \epsilon/d < 0.0234$ and $0.0325 < \epsilon/d < 0.0468$

The tendency for C_D of a roughened cylinder to become independent of e/d as the relative roughness increases is shown in Figures 44 and 45, and this trend agrees with that reported by Jones (12). In the free stream the surface roughness of a cylinder causes the boundary layer of the cylinder to become turbulent at lower Reynolds numbers than for a smooth cylinder, with a resulting lower C_D . Figure 52 indicates that for the relative roughnesses used the Reynolds number range investigated is in the critical to supercritical flow regions; therefore, the cylinder boundary layer is turbulent. This roughness effect causes the elimination of the peaking of C_D in the range of e/d of 1.25 to 0.625 for the case of a smooth cylinder.

5.3 Coefficient of Lift for a Smooth Cylinder

The coefficient of lift shown in Figure 40 agrees well with that reported by Tivolacci (27) and Ippen (11) shown in Figure 10, except for the Reynolds number range of 2×10^4 to 3×10^4 . In

this range the forces exerted on the test cylinder are near the lower measurable limit of the force dynamometer system employed, and some distortion of the data probably occurs. It is important to note that the trend established for the higher Reynolds number ranges is reflected in the Reynolds number range of 2×10^4 to 3×10^4 .

The lift on a cylinder becomes increasingly important as the cylinder nears the plane boundary. In this experimental work the boundary layer on the plane boundary is small, and it has little influence on the results. As the boundary layer increases to the order of magnitude of the cylinder diameter a much different condition is encountered since the flow is no longer uniform but varies within the boundary layer as a function of the height away from the boundary. The coefficients of lift and drag are dependent not only on ρ , d , U , and ν as when the cylinder is in the free stream, but also, as shown by Jones (12), on those quantities which affect the shape of the boundary layer profile. The coefficient of lift for a cylinder immersed in a boundary layer as a function of e/d is shown in Figure 53 from the work done by Jones.

5.31 Fluctuating Lift

The purpose of this thesis is to investigate the net lift force exerted on the cylinder due to the proximity of a plane boundary; therefore, the data extracted from the lift force recordings are an

average peak to peak value which gives only the net lift force on the cylinder. The fluctuations noted on the recordings, typified by those shown in Figures 21 and 22, are a combination of mechanical vibrations and fluctuating lift. The measurement system was not designed to quantify the magnitude of the fluctuating lift; therefore, neither a quantitative nor qualitative interpretation of the fluctuating lift can be made from the experimental data.

5.32 Influence of Separation and Stagnation Points

As discussed in references (27) and section 2.24, the location of the separation and the stagnation points on the cylinder play an important role in the lift force experienced by the cylinder. In Figure 46 the stagnation point plotted as a function of e/d is compared with previous experimental data and the potential flow theory, and there is fairly good agreement. The point of stagnation is below the free stream stagnation point for the range $0.0625 < e/d < 1.5$; therefore, a lift is to be predicted, which is observed in Figure 40.

The relative separation points plotted in Figure 47 compare well with the results of reference (27) with respect to the characteristics of the curves. The experimental data do show a notable exception from that of reference (27), wherein there is a sudden decrease and increase in the angle at which the upper separation occurs in the range $0.75 < e/d < 1.25$. This reversing motion causes the wake to

increase and then decrease on the upper portion of the cylinder, resulting in a sudden low pressure differential. This results in a sudden upward lift on the cylinder away from the plane boundary; a result that is observed to occur as seen in Figures 10 and 40.

5.4 Coefficient of Lift for Roughened Cylinders; 0.0165 < ϵ/d < 0.234 and 0.0325 < ϵ/d < 0.0468

It is noted from Figures 41 and 42 that the effect of cylinder surface roughness is to eliminate the sudden increase in lift shown in Figure 40 for a smooth cylinder at an e/d of about 1.125. The magnitude of the lift force near the plane boundary is approximately that for a smooth cylinder; however, for both roughness conditions the lift force attenuates rapidly to zero as the cylinder moves away from the plane boundary.

5.5 Boundary Layer Separation on the Plane Boundary

Tavalocci in reference (27) indicated that the boundary layer on the plane boundary separated at some distance downstream from the cylinder; the distance being a function of the relative gap, e/d . Photographic data as well as visual observations did not confirm the existence of this separation. It is observed that when a vortex is shed from the bottom of the cylinder the vortex action pulls the boundary layer of the plane boundary into the wake region, as seen in Figures 32 through 39, giving rise to an apparent separation

downstream from the cylinder. When a vortex is shed from the upper portion of the cylinder a downwash is induced, and the lifting of the boundary layer of the plane boundary away from the plane boundary does not occur. The appearance of the apparent separation is periodic and a characteristic of the nearness of the plane boundary and the periodicity of vortex shedding.

6.0 APPLICATION OF RESULTS

In an ocean environment where a pipeline or cable is in deep enough water, such that only a relatively steady current is present, the lift and drag forces on the circular members which are near the bottom need to be known for design purposes. Although an effort is made in many installations of cables or pipelines to bury them and avoid the flow induced forces, many bottom geographies necessitate either laying the pipe or cable on the bottom, anchoring them in contact with the bottom, or anchoring them at some elevation above the bottom.

From Figures 54 and 55 it can be concluded that extremely adverse lift and drag forces will be experienced by a smooth circular member if the gap to diameter ratio is in the interval $0.5 < e/d < 1.25$. Ideally, to avoid a net upward lift, the member should be placed at least two diameters away from the bottom or buried; however, in most cases this is not only impractical but impossible. It is then desirable to have the member in the interval $0.0 < e/d < 0.5$. In this interval, depending on the surface roughness of the member, the curves of Figures 54 and 55 give conservative values of C_D and C_L based on the data presented in this thesis. For roughened cylinders C_D increases with increasing Reynolds number and C_L decreases with increasing Reynolds number; therefore, Figure 54 gives a conservative value of C_L for $R_e > 70,000$, but the value of C_D at

$R_e > 80,000$ for a roughened cylinder can only be estimated from the curve of Figure 55 for the upper limit for a smooth cylinder.

It should be noted that the C_D and C_L curves do not take into consideration the fluctuating lift or drag on the cylinder. The readings taken to obtain the data were averaged readings; therefore, if the fluctuating lift and drag are such that their magnitude is significant, then the values of C_D and C_L taken for design from the curves of Figures 54 and 55 should be modified accordingly.

Prior to utilizing Figures 54 and 55 as design curves, it must be observed that the data reported in this thesis is by no means exhaustive. Depending on the dollar value of a proposed installation, experimentation may be warranted to further verify the range of the C_L and C_D curves. If the curves in Figures 54 and 55 are utilized to obtain design values of C_L and C_D the upper limit for a smooth cylinder should be used in both figures. Since exposure to an ocean environment will eventually roughen a pipeline or cable installation, conservative values of C_D and C_L will be obtained from Figures 54 and 55. A factor of safety should still be applied to the magnitude of C_D and C_L ; the magnitude of this factor of safety depending on the limiting maximum cost for the system.

7. 0 CONCLUSIONS

1. 0 Smooth Cylinder Drag Coefficient: For this experimentation a net decrease in the coefficient of drag of approximately 15% from that observed in the free stream is experienced by a smooth cylinder at the plane boundary. For the interval $0.625 < e/d < 1.25$ there is a sudden increase in the drag coefficient of from 20% to 60% over the free stream value, depending on the Reynolds number of the flow, with a peak value of the coefficient at an e/d of about 0.875.

2. 0 Smooth Cylinder Lift Coefficient: The coefficient of lift for a smooth cylinder near a plane boundary decreases rapidly with increasing e/d . In the interval $0.75 < e/d < 1.25$ a sudden increase in the coefficient of lift is experienced with a peak value at an e/d of about 1.125. This sudden increase in lift is apparently due to the reversing nature of the upper separation point between an e/d of 0.75 and 1.25. The coefficient of lift for a specific value of e/d has a general tendency to diminish as the Reynolds number of the flow increases in the subcritical range $20,000 < R_e < 70,000$.

3. 0 Boundary Layer on the Plane Boundary: Separation of the boundary layer on the plane boundary downstream from the cylinder as the cylinder approaches the plane boundary was not observed to occur.

4.0 Cylinder Surface Roughness: $0.0165 < \epsilon/d < 0.0234$ and $0.0325 <$

$\epsilon/d < 0.0468$; The effect of cylinder surface roughness is to eliminate the sudden peaking of the coefficients of lift and drag experienced by a smooth cylinder in the range $0.75 < e/d < 1.25$.

5.0 Strouhal Number: For this experiment the Strouhal number for

a smooth cylinder as it approaches a plane boundary increases from the free stream value for the range $0.875 < e/d < 1.5$ and decreases for the range $0.0625 < e/d < 0.875$. Based on the constant wake Strouhal number presented by Roshko (22), a definite correlation exists between the vortex shedding frequency and the drag force on a smooth circular cylinder as the cylinder approaches a plane boundary.

8.0 FIGURES



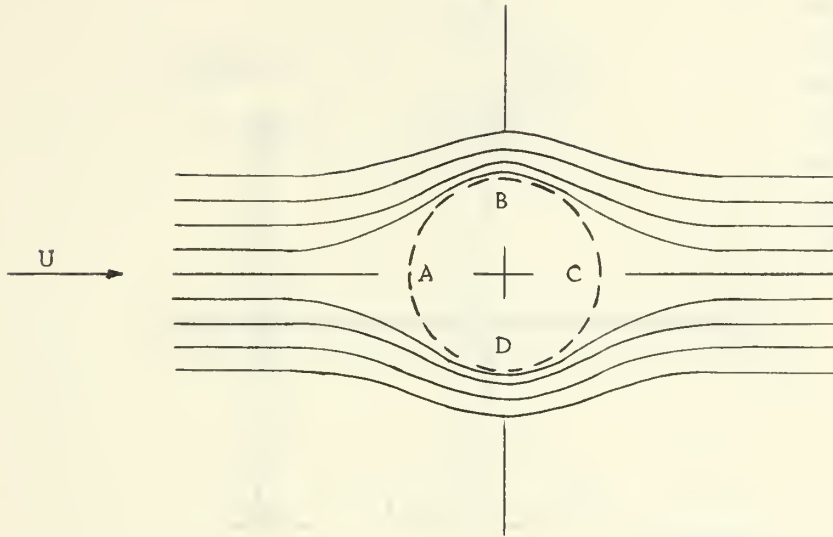


Figure 1. Streamlines for Steady, Two Dimensional Potential Flow.

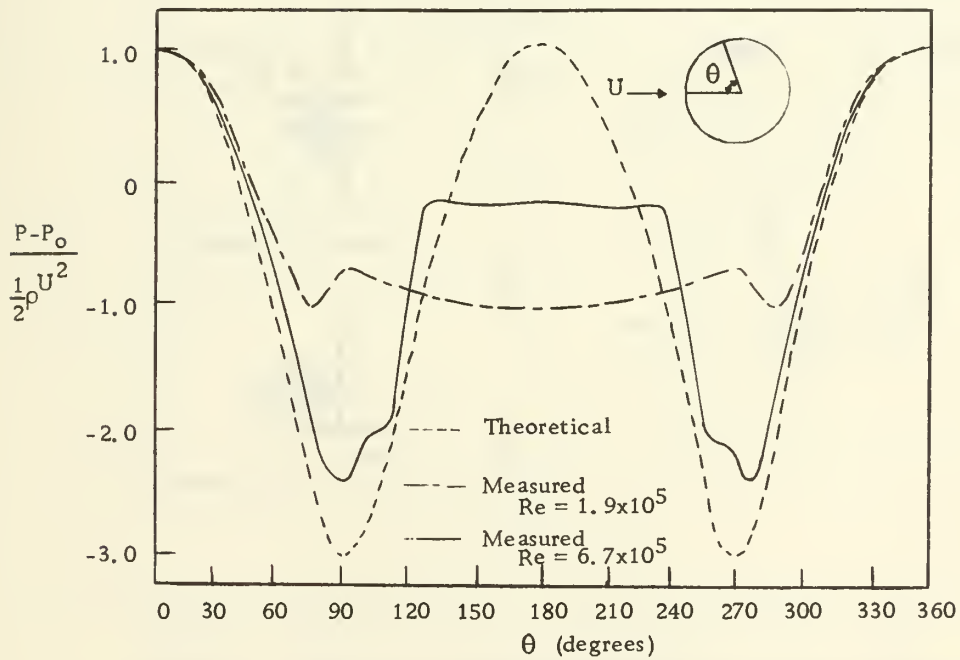


Figure 2. Pressure Coefficient as a Function of $\theta(10)$.

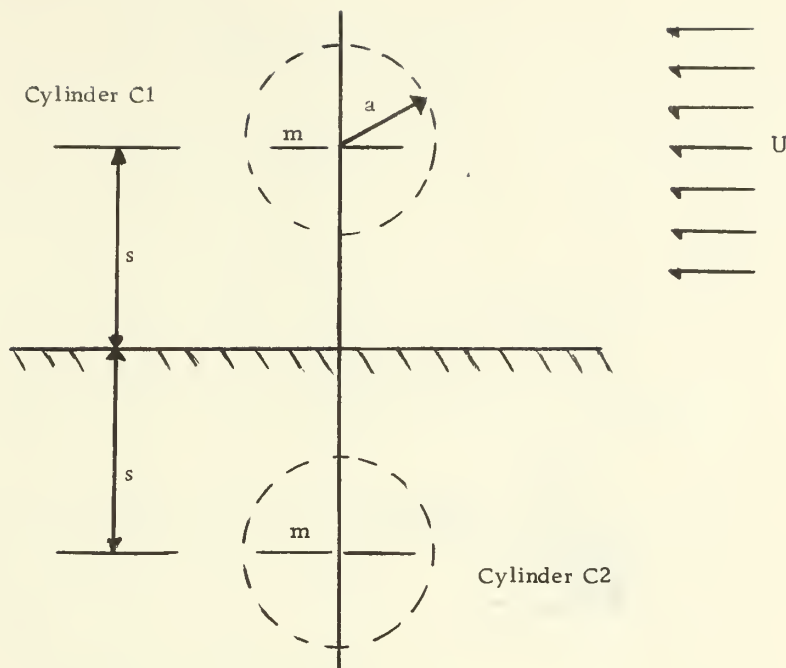


Figure 3. Circular cylinder near a plane boundary (27)

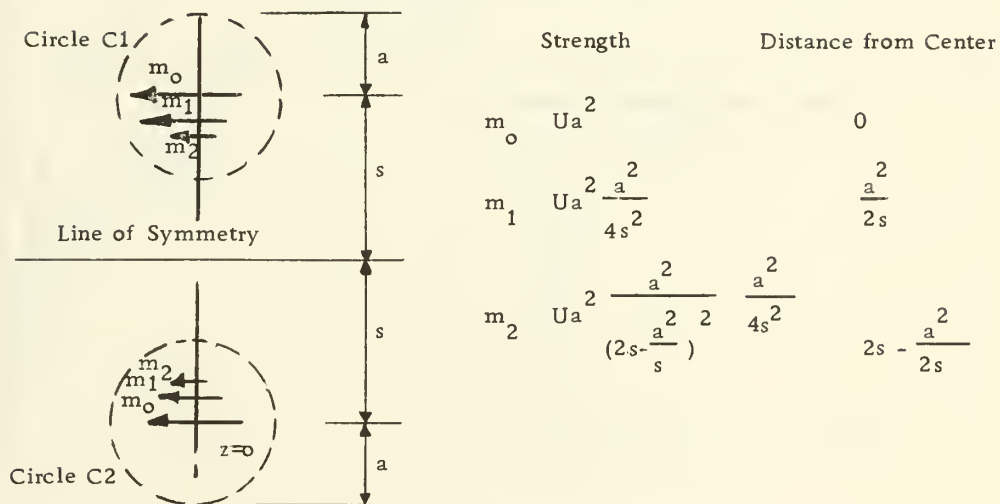


Figure 4. Distribution of Doublets for Uniform Flow past Two Cylinders (27).

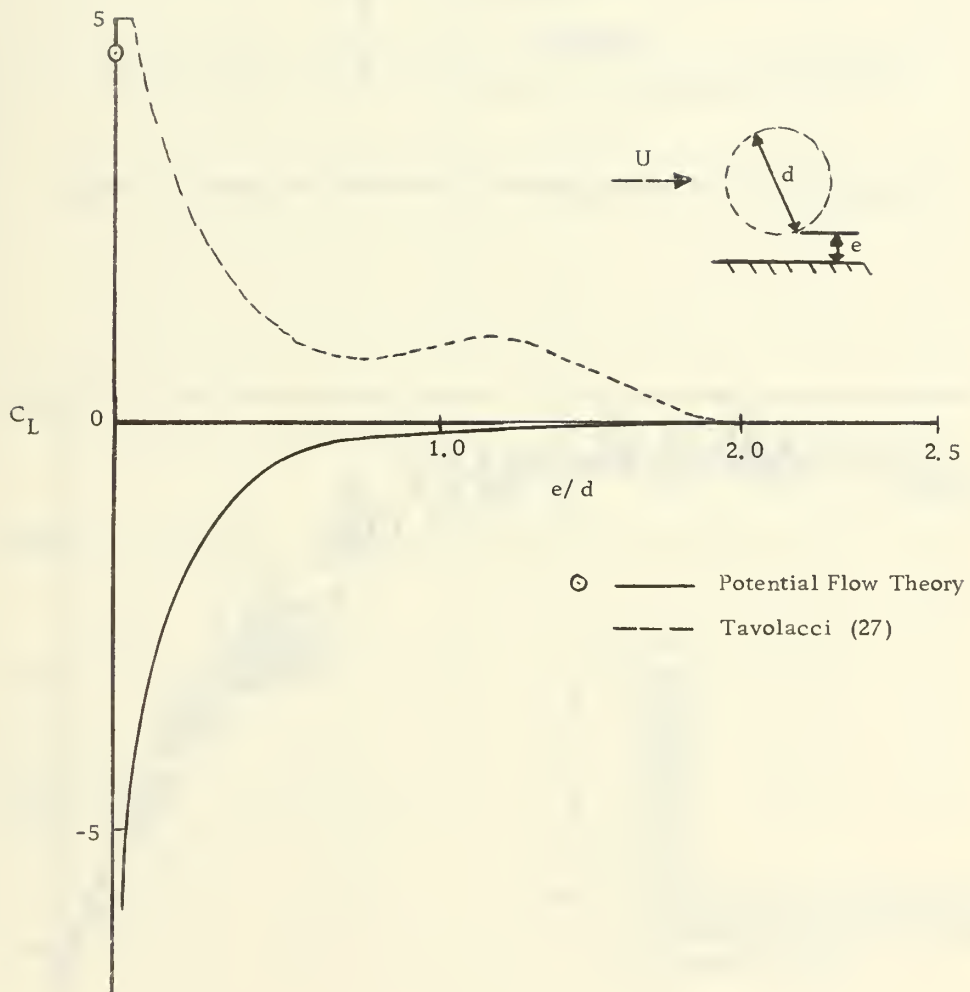


Figure 5. Lift Coefficient for a Smooth Cylinder by Potential Flow Theory and Experimentation (28).

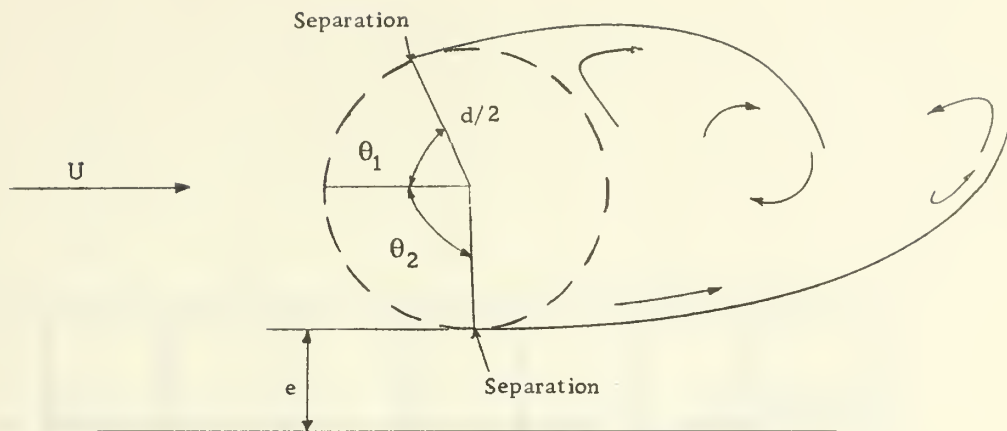


Figure 6. Asymmetric Wake Behind a Smooth Cylinder Near a Plane Boundary.

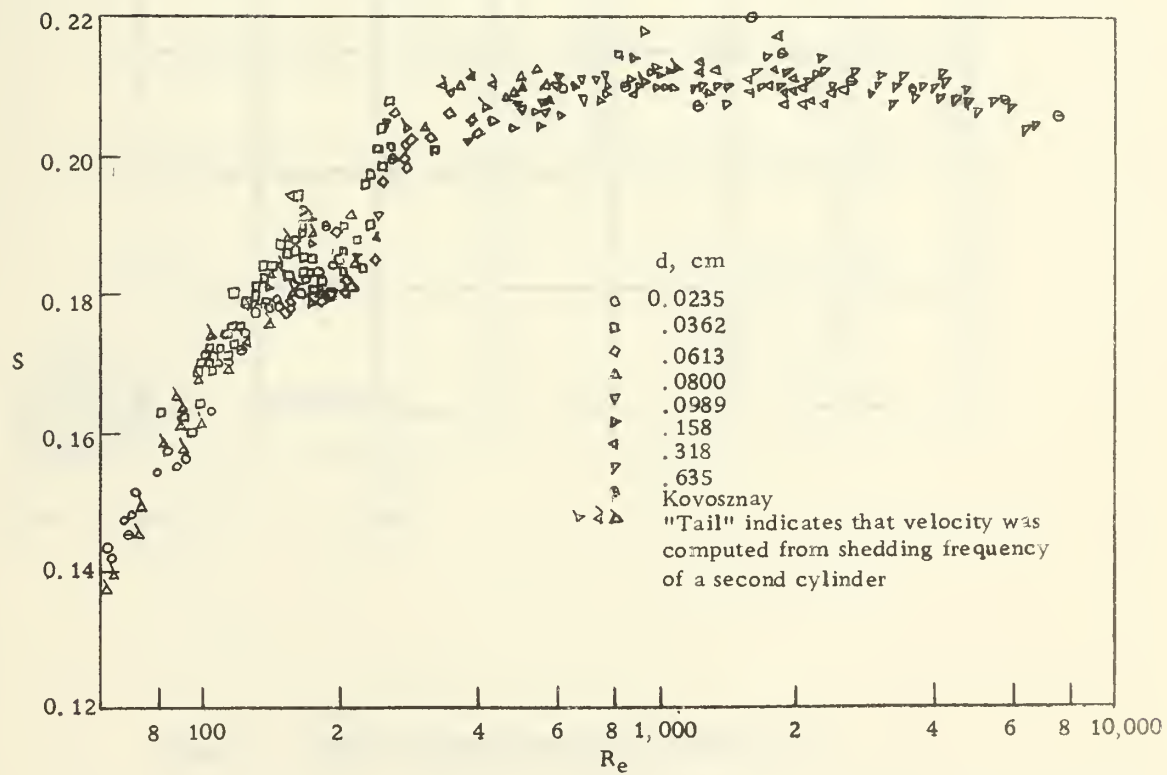


Figure 7. Strouhal Number as a Function of Reynolds Number for a Smooth Circular Cylinder, (20).

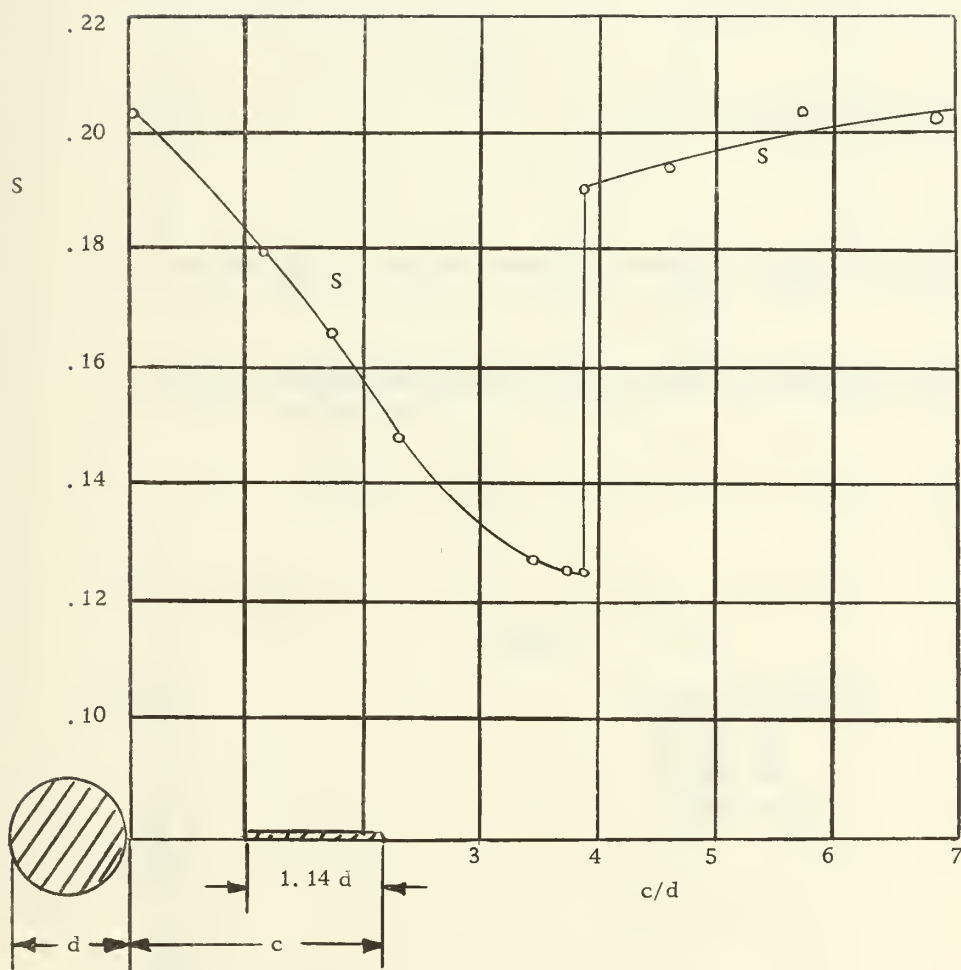


Figure 8. Splitter Plate Wake Interference Element (21).

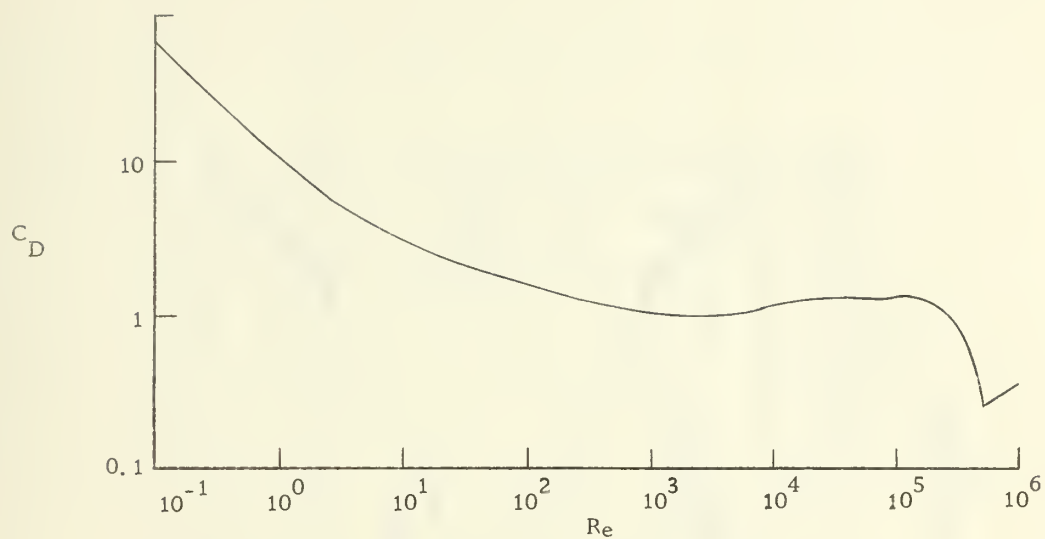


Figure 9. Drag Coefficient for Circular Cylinders as a Function of the Reynolds Number (24)

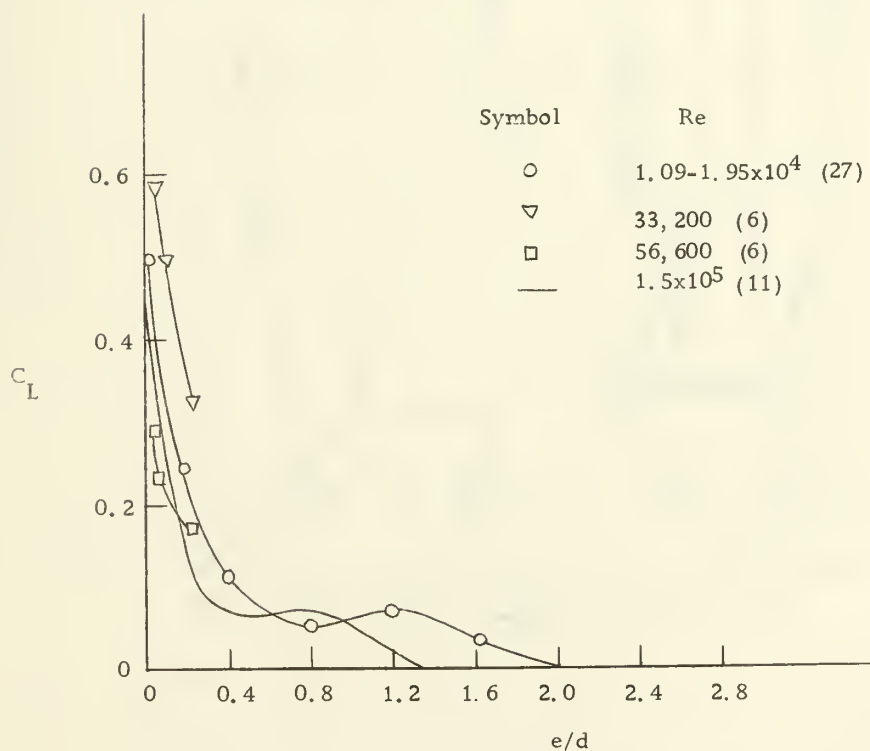


Figure 10. Lift Coefficient for Smooth Circular Cylinders as a Function of e/d .

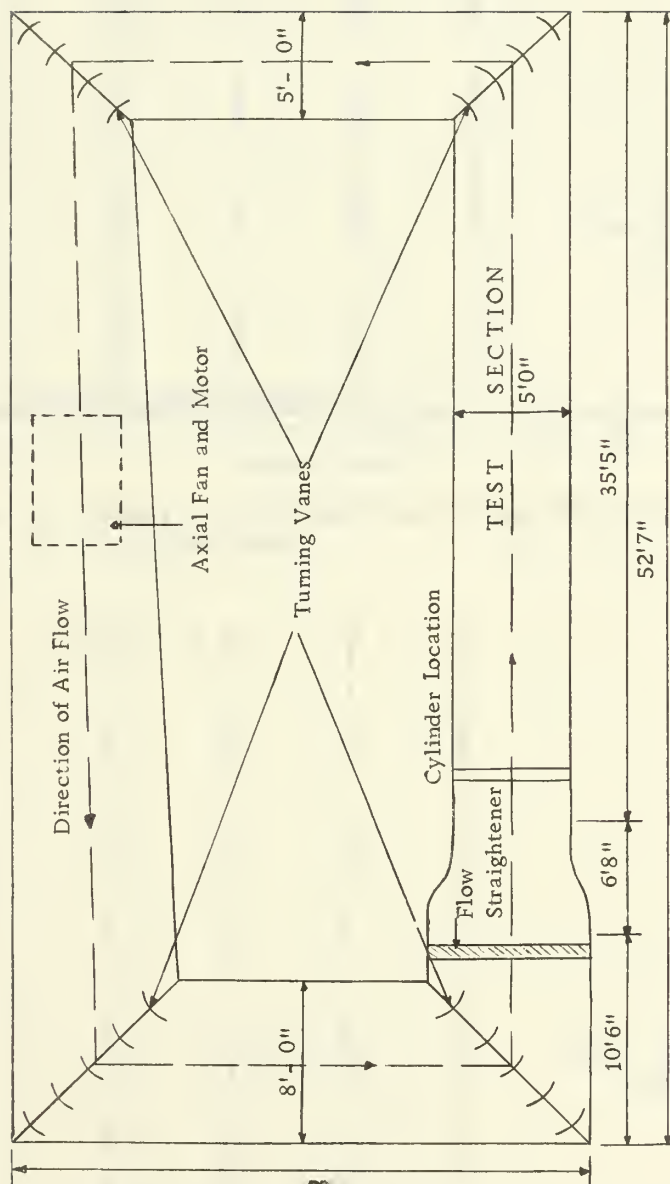


Figure 11. Plan View O. S. U. Low Velocity Wind Tunnel.

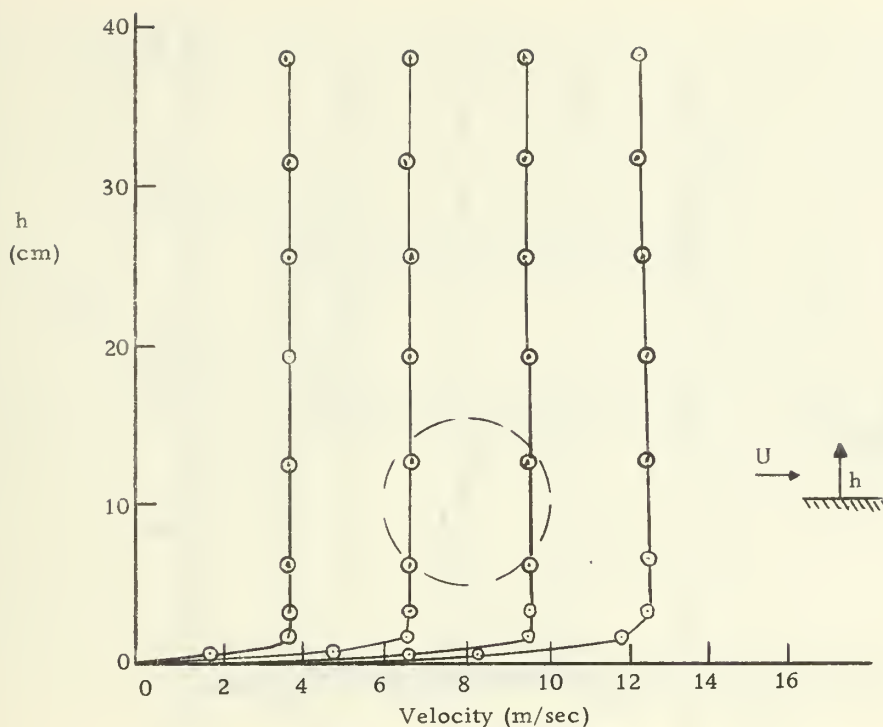


Figure 12. Velocity Profiles in Wind Tunnel at Right End of Test Section as Viewed from Upstream.

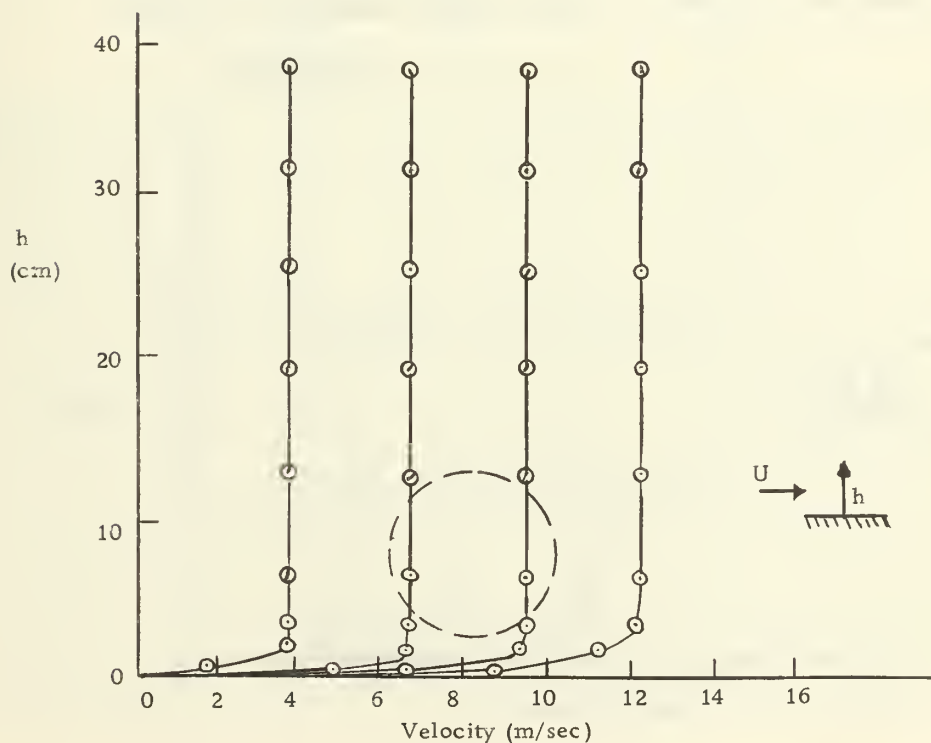


Figure 13. Velocity Profiles in Wind Tunnel at Left End of Test Section as Viewed from Upstream.

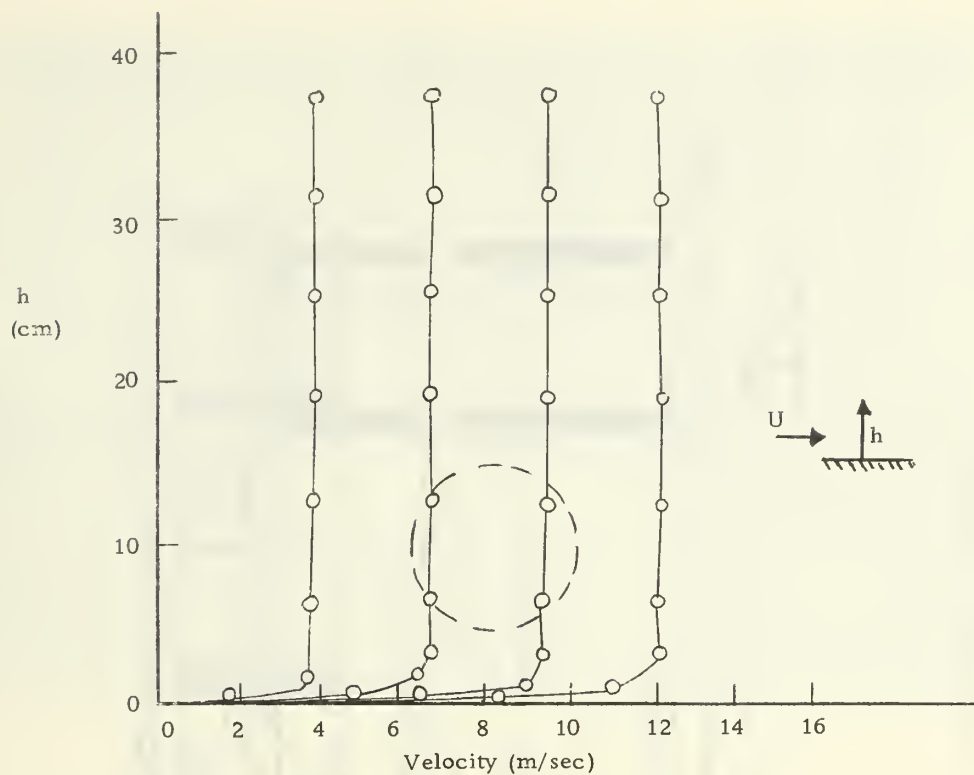


Figure 14. Wind Tunnel Velocity Profiles at Centerline of Test Section Location.

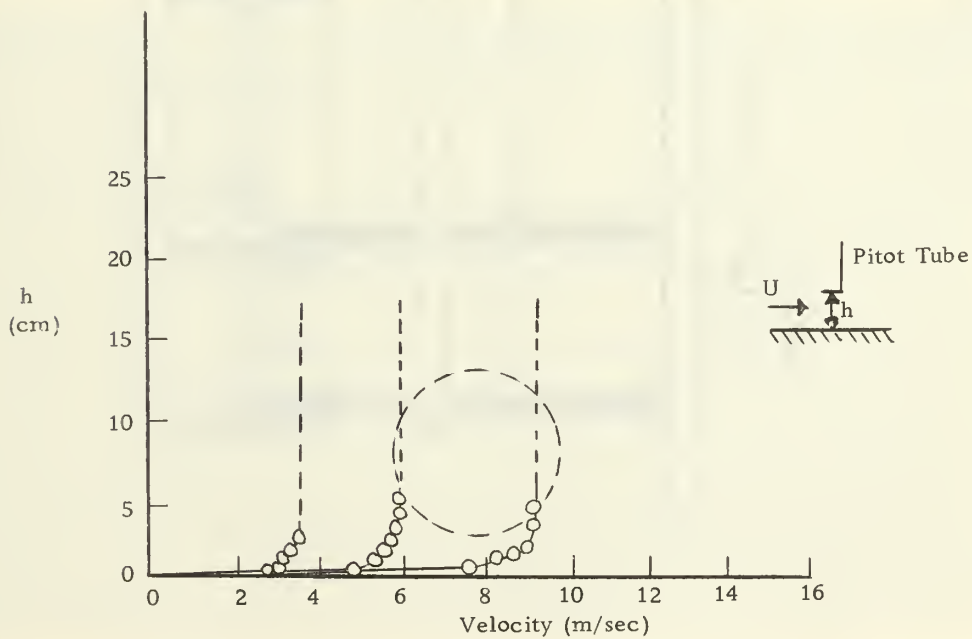


Figure 15. Boundary Layer Velocity Profiles in Wind Tunnel (Average Values Taken Along Length of Test Section).

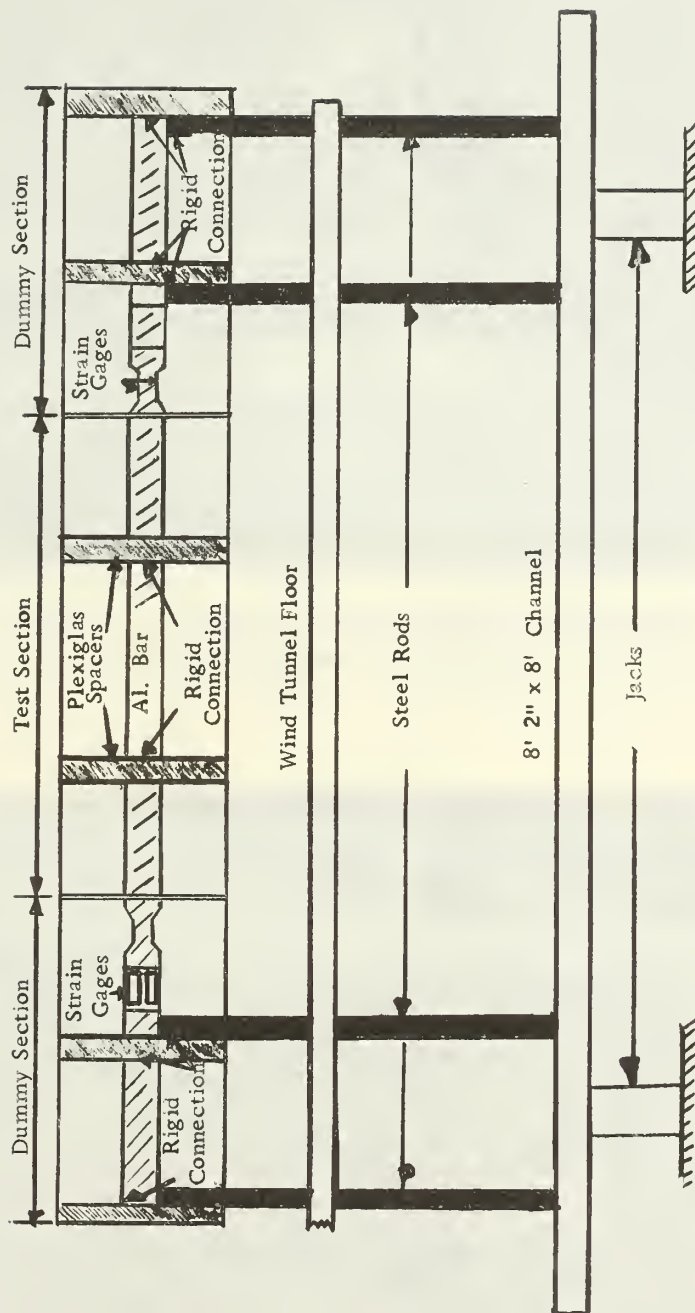


Figure 16. Elevation View of Test Cylinder in Wind Tunnel.

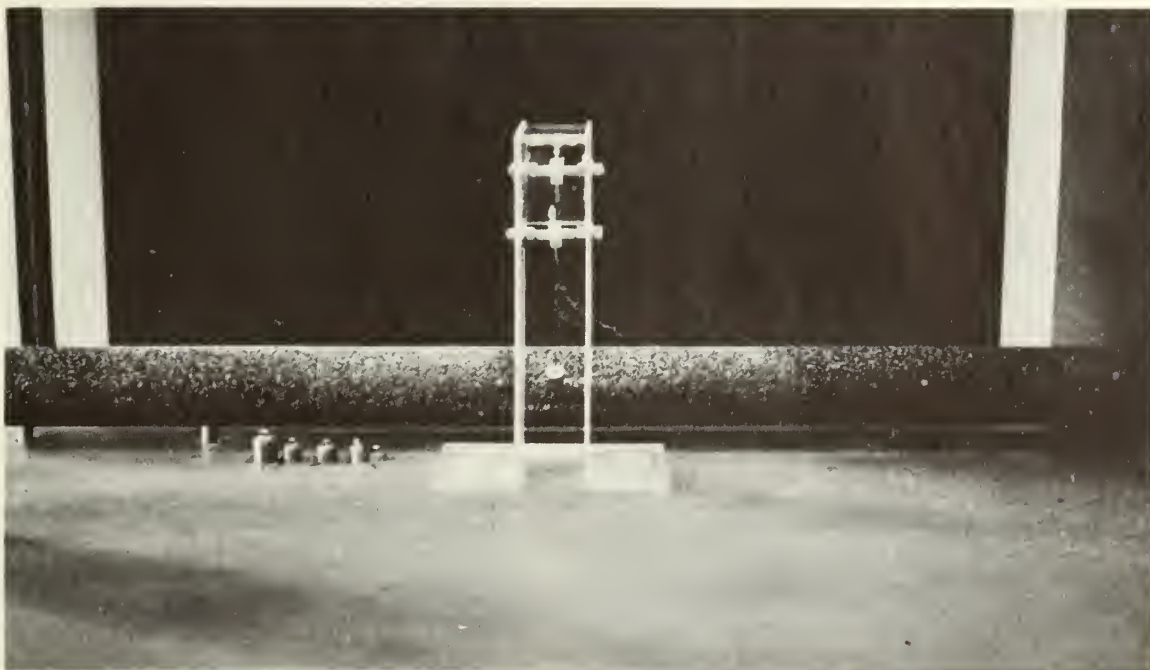


Figure 17. Roughened Cylinder Mounted in Wind Tunnel with Calibration Pulley System.

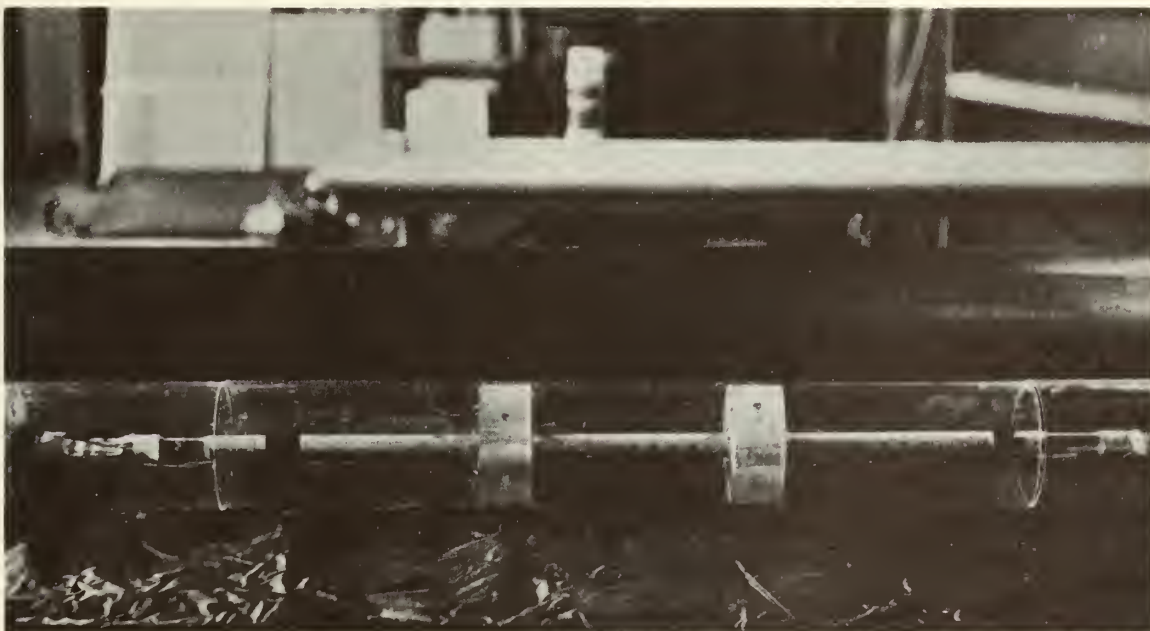


Figure 18 Strain Gage Attachment and Joint Between Test Section and Dummy Section.

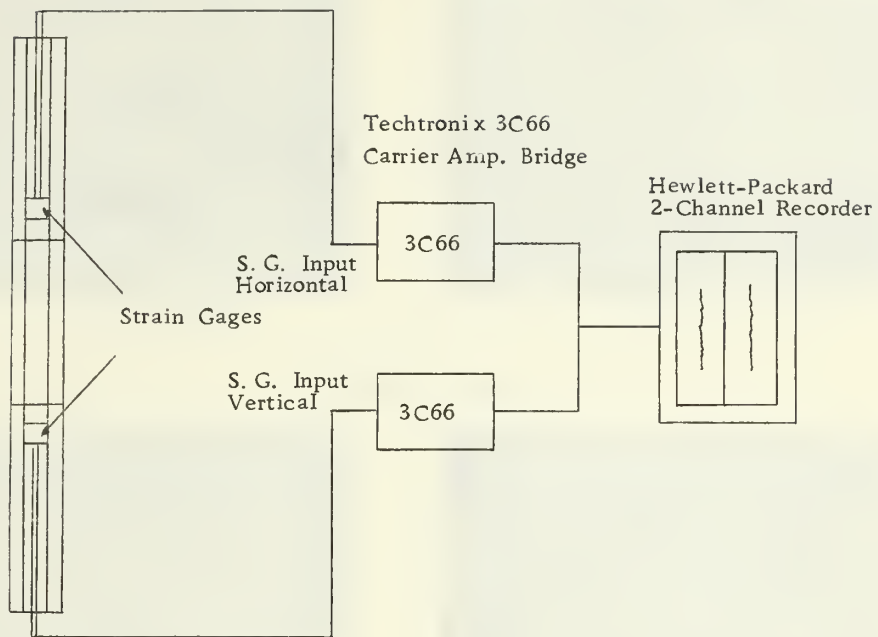


Figure 19. Strain Gage Measurement Flow Chart

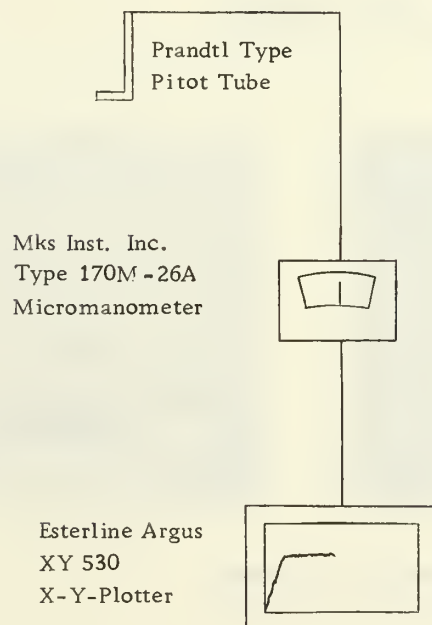
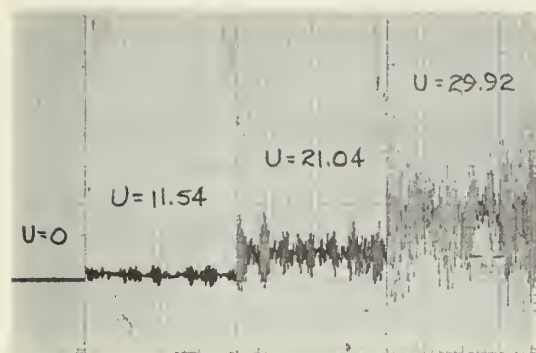
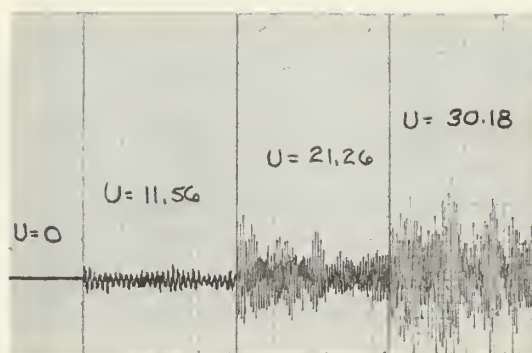


Figure 20. Differential Pressure Measurement Flow Chart.

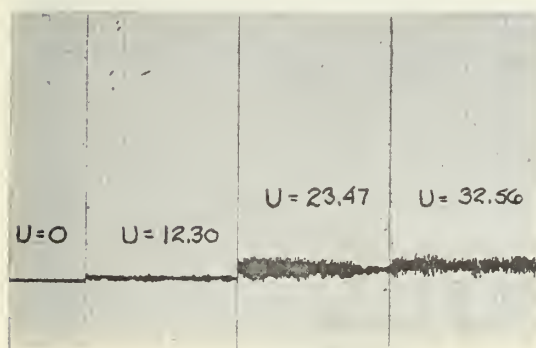


$e/d = 0.0625$

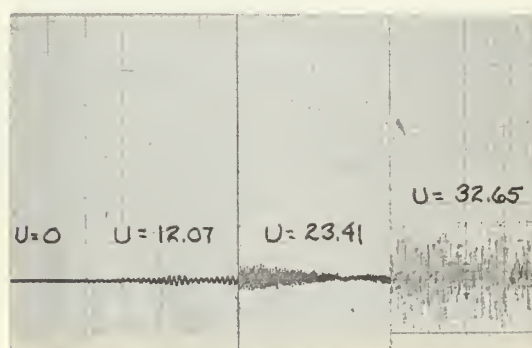


$e/d = 1.0$

Smooth Cylinder

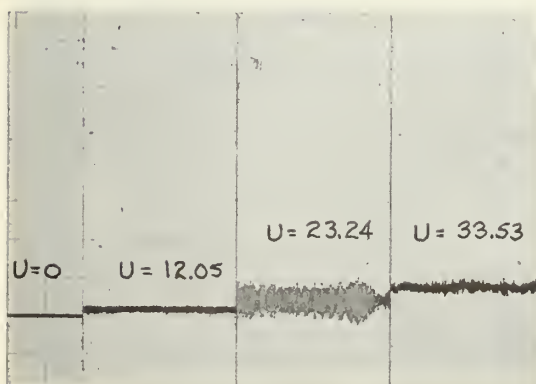


$e/d = 0.0625$

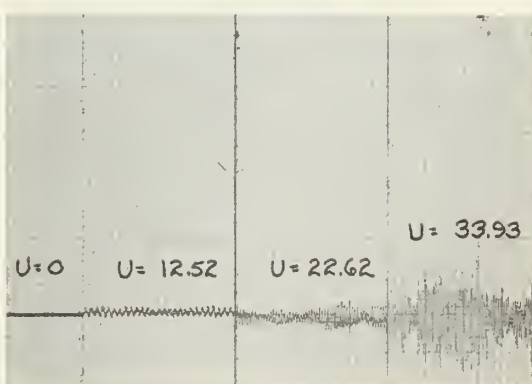


$e/d = 0.75$

Roughened Cylinder
 $0.0165 < \epsilon/d < 0.0234$



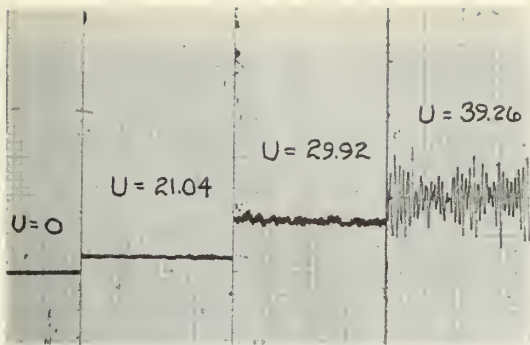
$e/d = 0.0625$



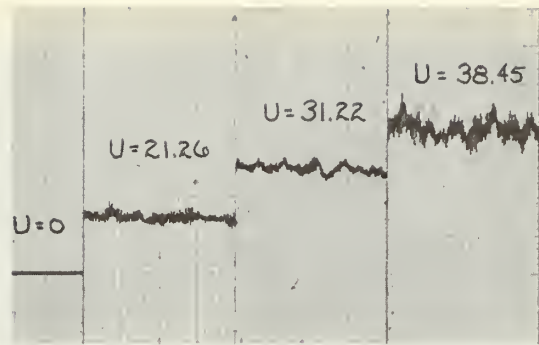
$e/d = 1.5$

Roughened Cylinder
 $0.0325 < \epsilon/d < 0.0468$

Figure 21. Strain Gage Readings of F_L for Smooth and Roughened Cylinders in the Wind Tunnel.

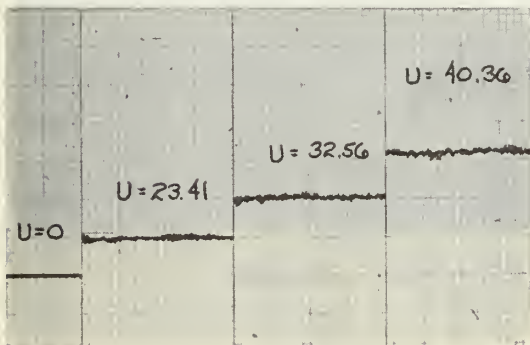


$e/d = 0.0625$

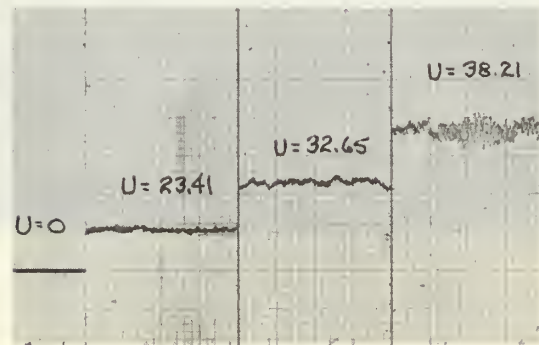


$e/d = 1.0$

Smooth Cylinder

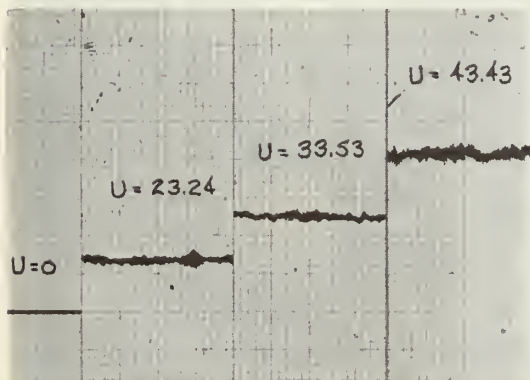


$e/d = 0.0625$

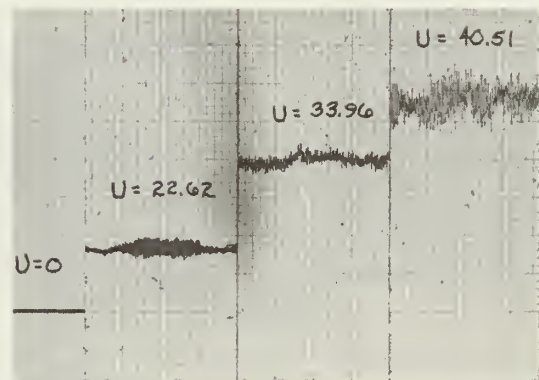


$e/d = 0.75$

Roughened Cylinder
 $0.0165 < \epsilon/d < 0.0234$



$e/d = 0.0625$



$e/d = 1.5$

Roughened Cylinder
 $0.0325 < \epsilon/d < 0.0468$

Figure 22. Strain Gage Readings of F_D for Smooth and Roughened Cylinders in the Wind Tunnel.

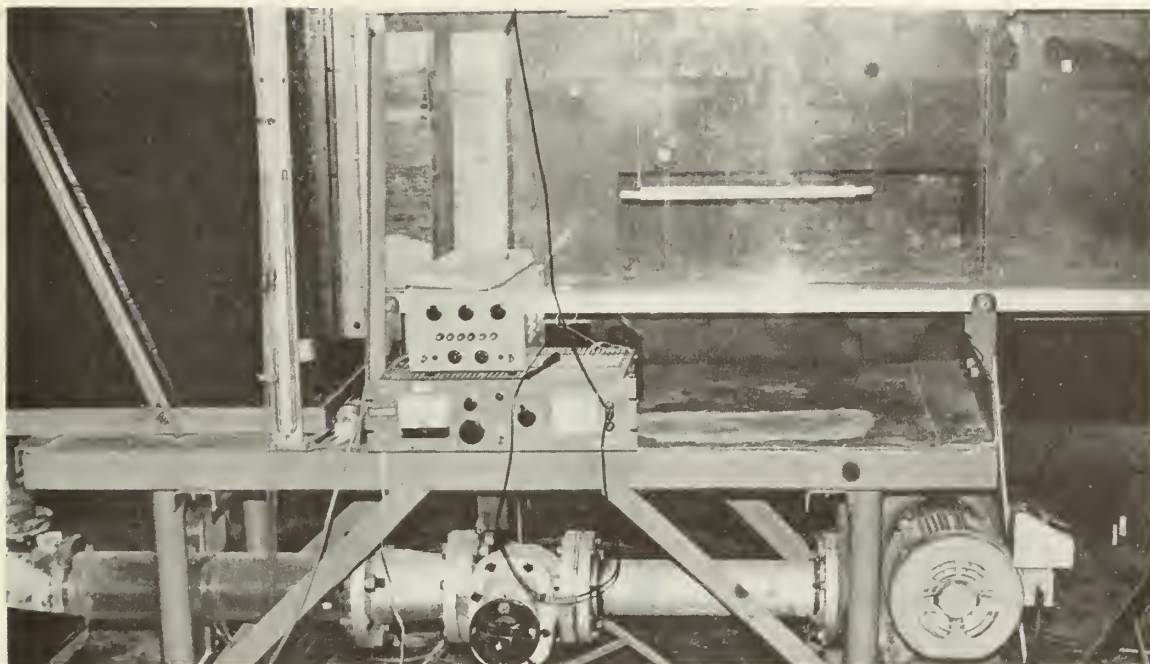


Figure 23. Recirculating Water Channel Test Section.

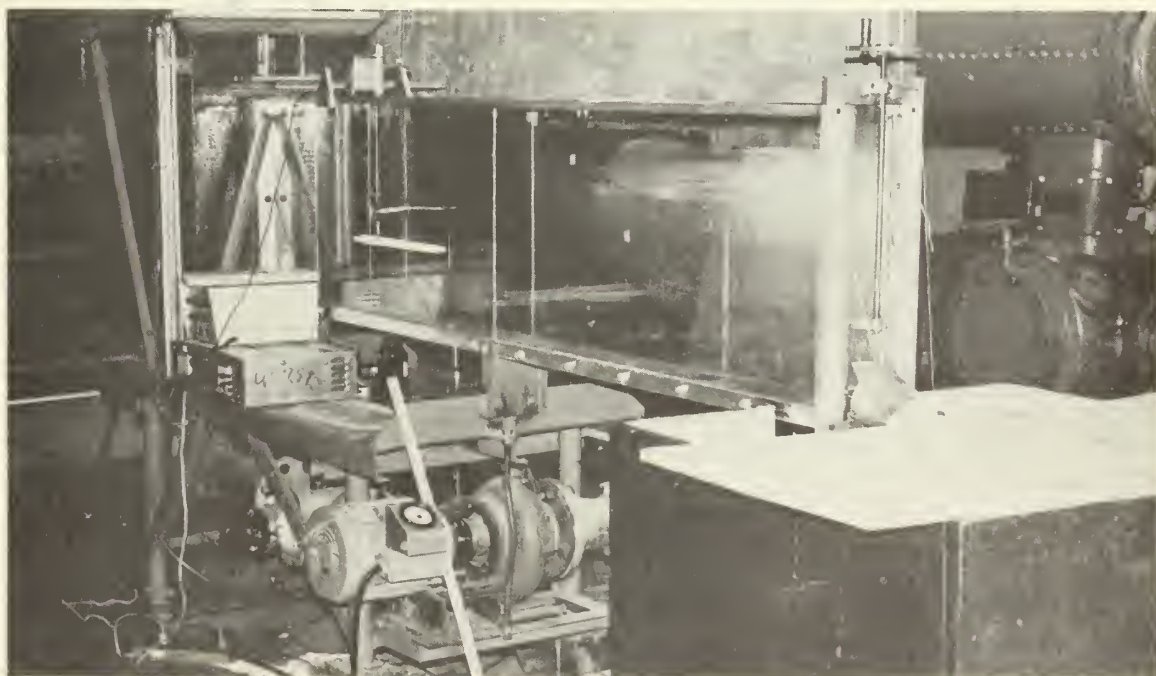


Figure 24. Recirculating Water Channel.

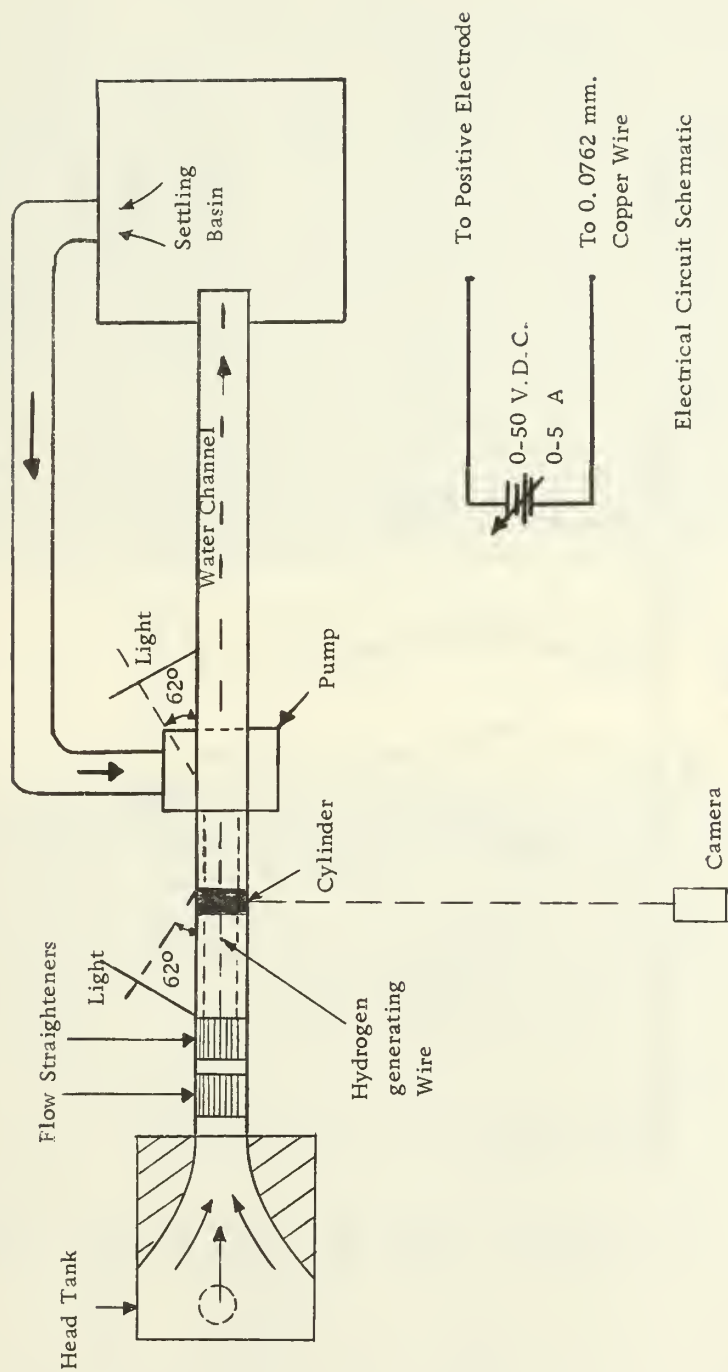


Figure 25. Plan View of Recirculating Water Channel.

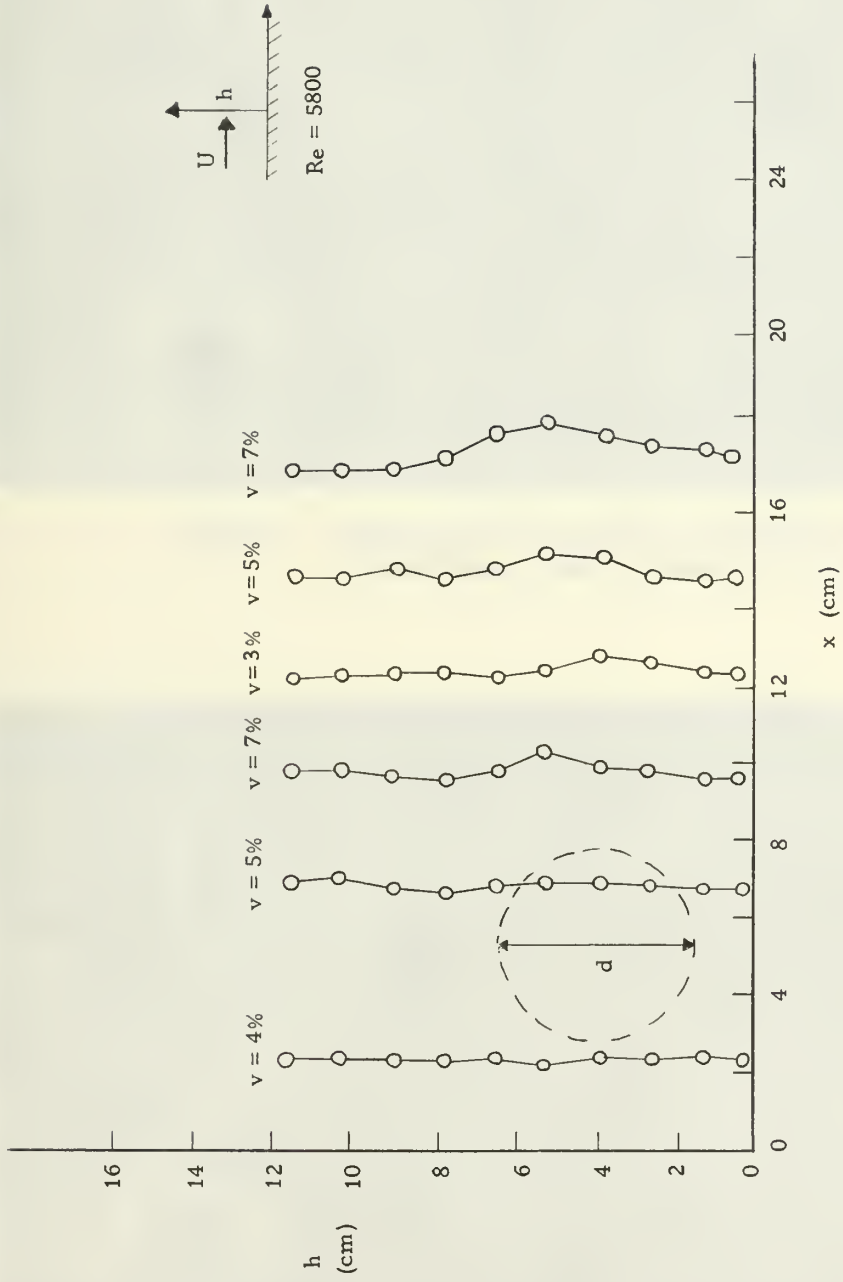


Figure 26. Spatial Flow Profiles in Water Channel.



Figure 27. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.0625$.



Figure 28. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.125$.

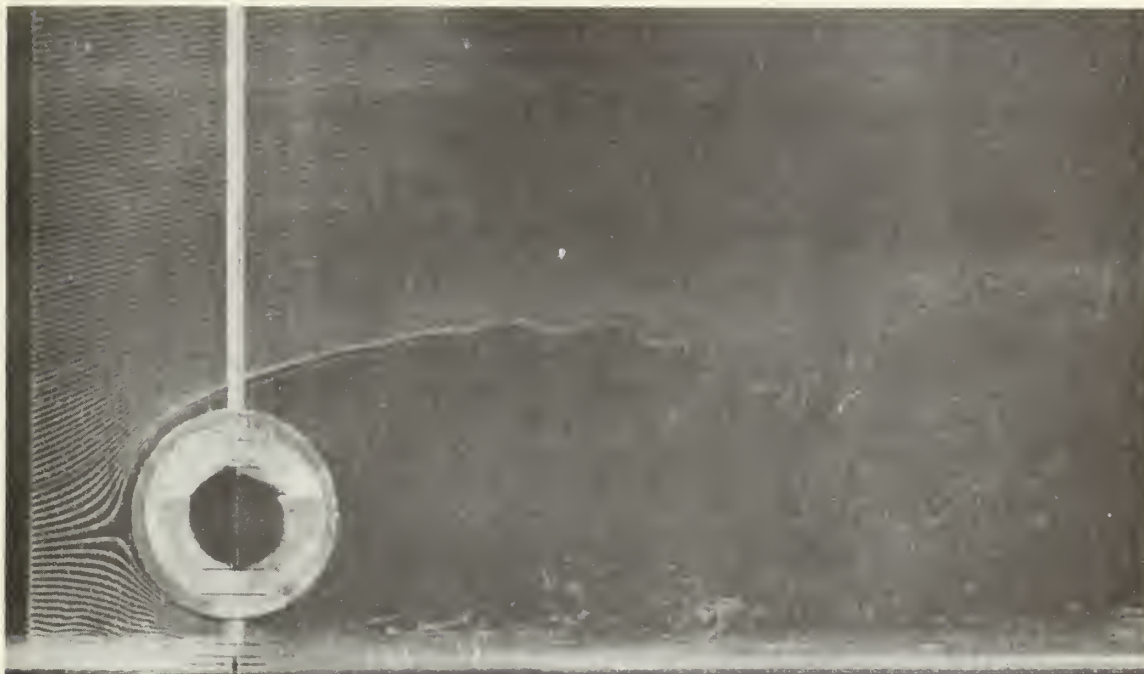


Figure 29. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.25$.

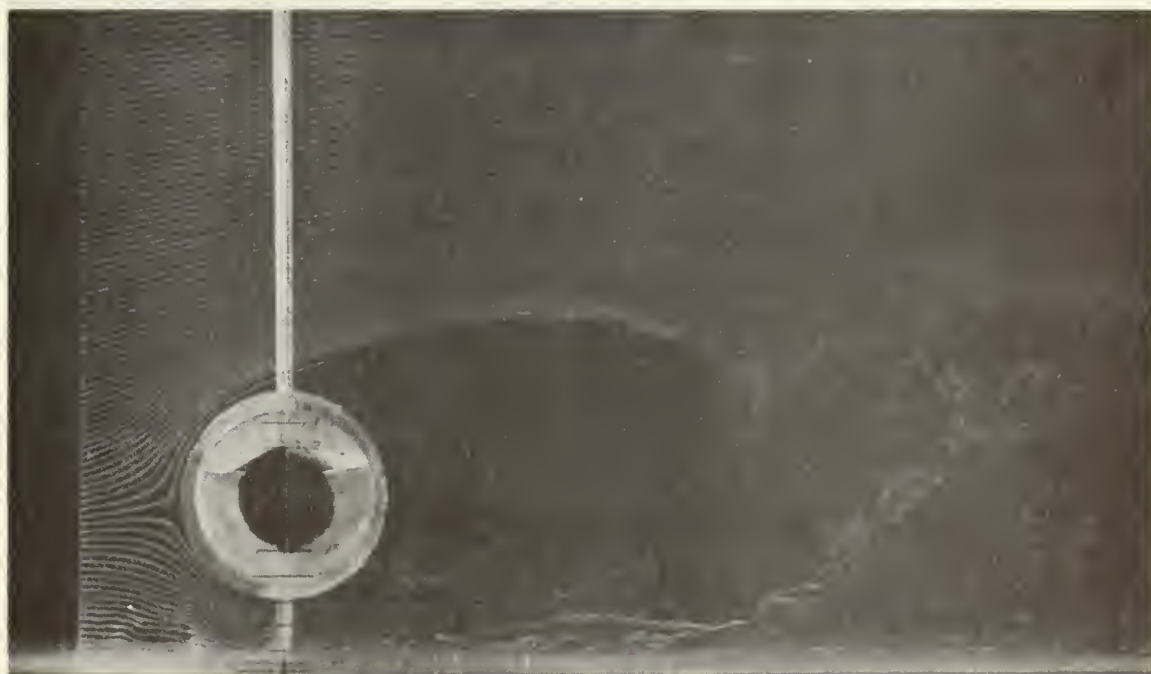


Figure 30. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder $e/d = 0.375$.

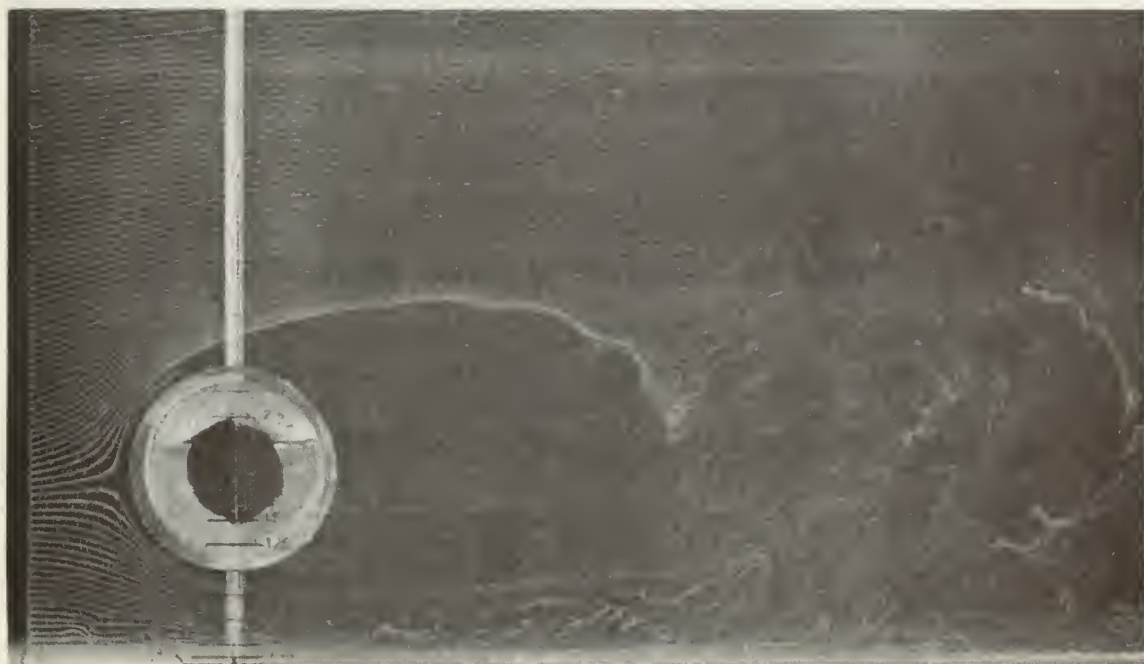


Figure 31. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.50$.



Figure 32. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.75$.

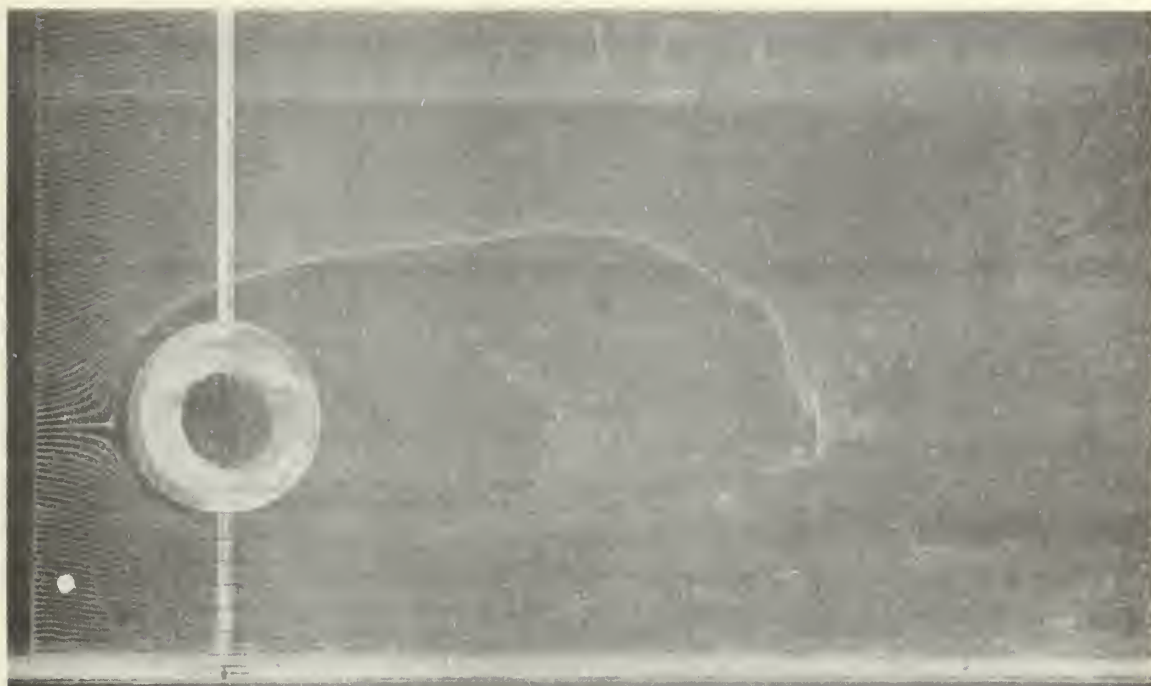


Figure 33. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 0.875$

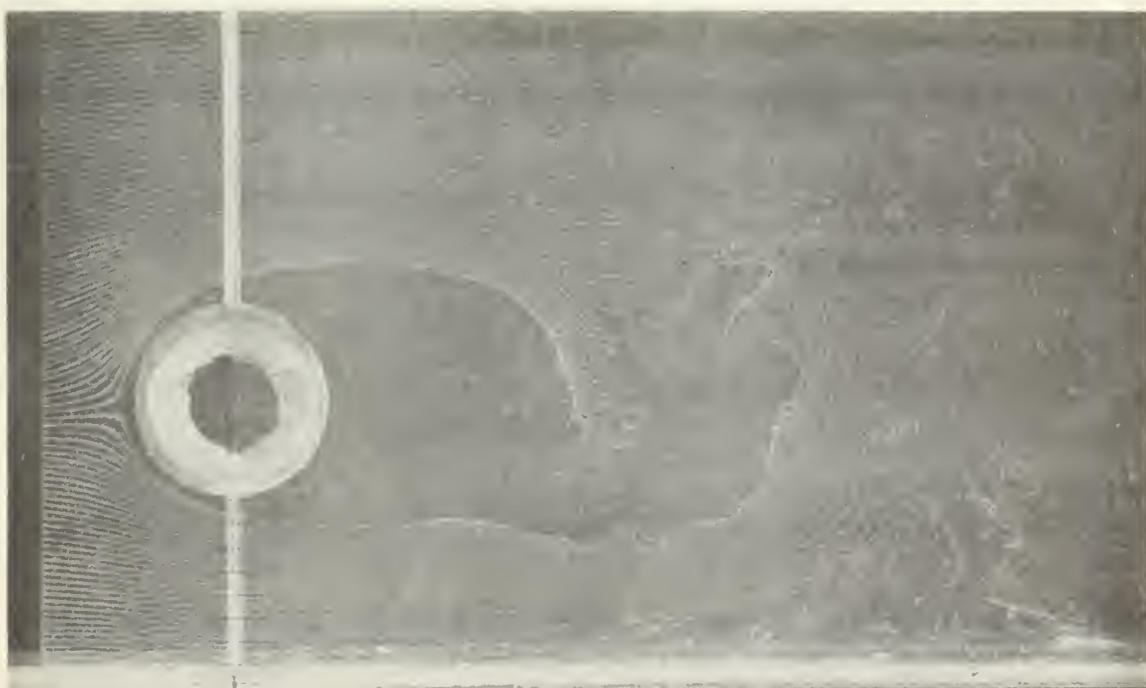


Figure 34. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.00$.

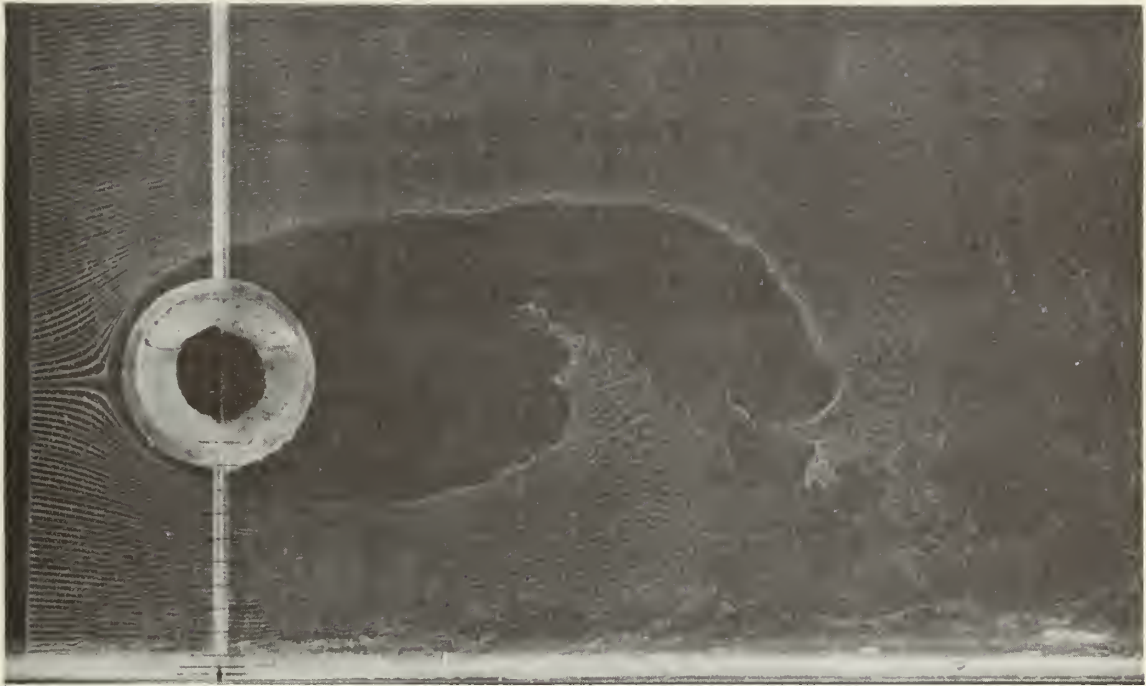


Figure 35. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.125$.

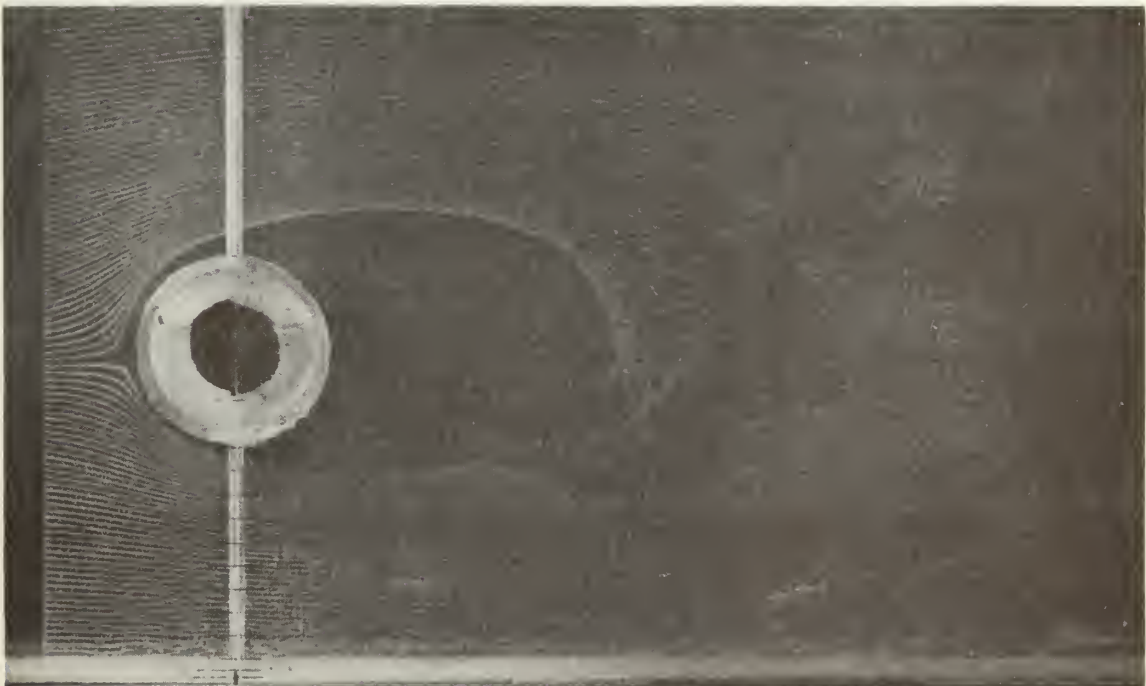


Figure 36. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.25$.

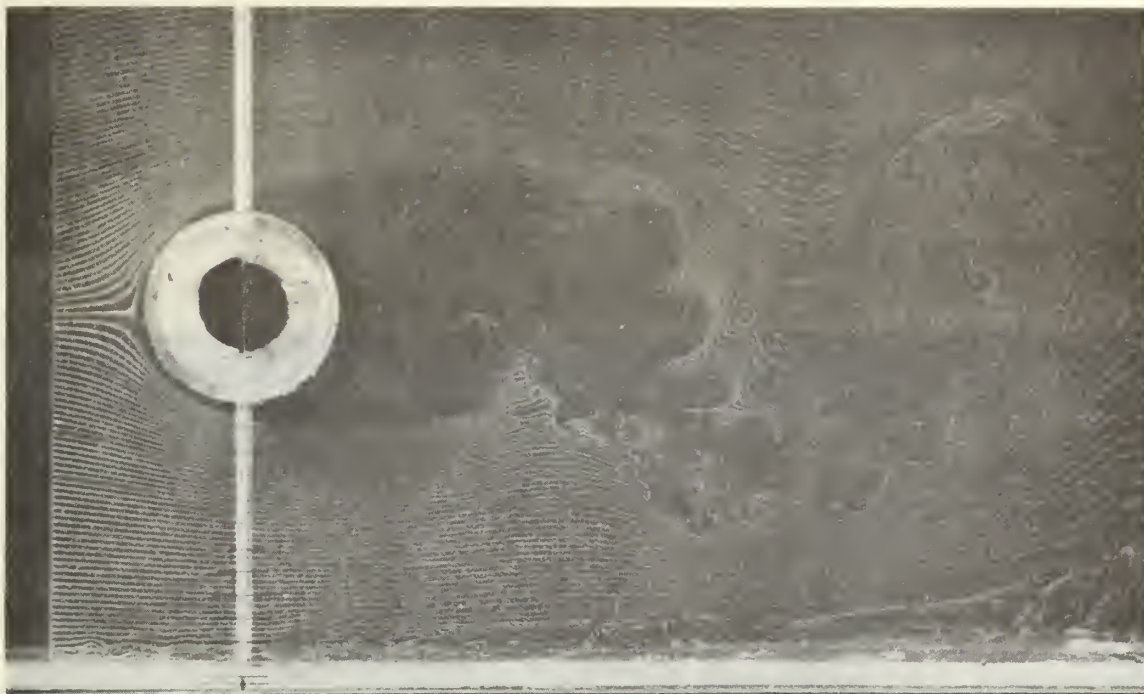


Figure 37. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.50$.

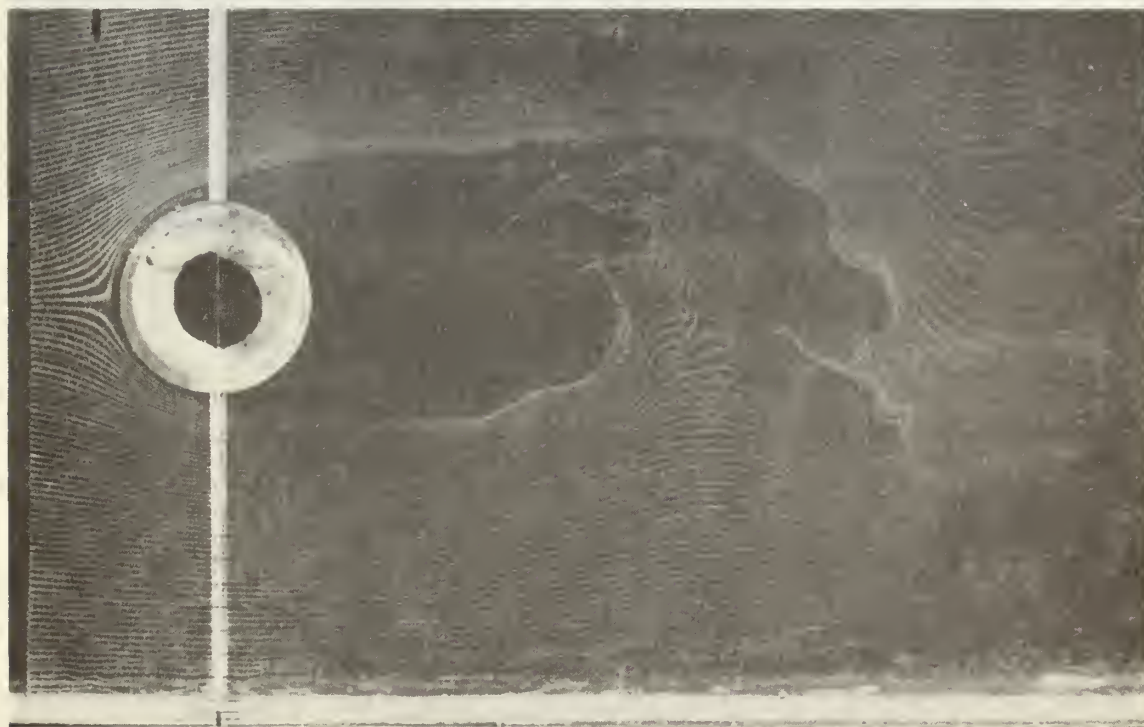


Figure 38. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 1.75$.

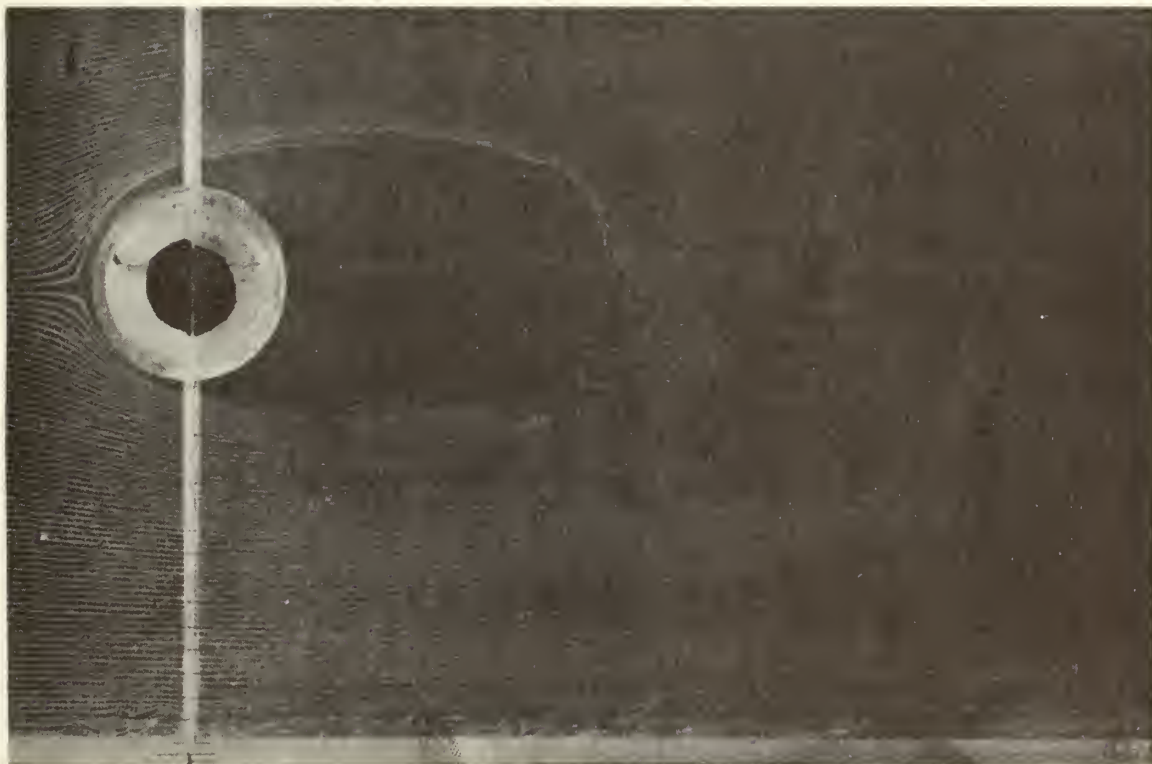
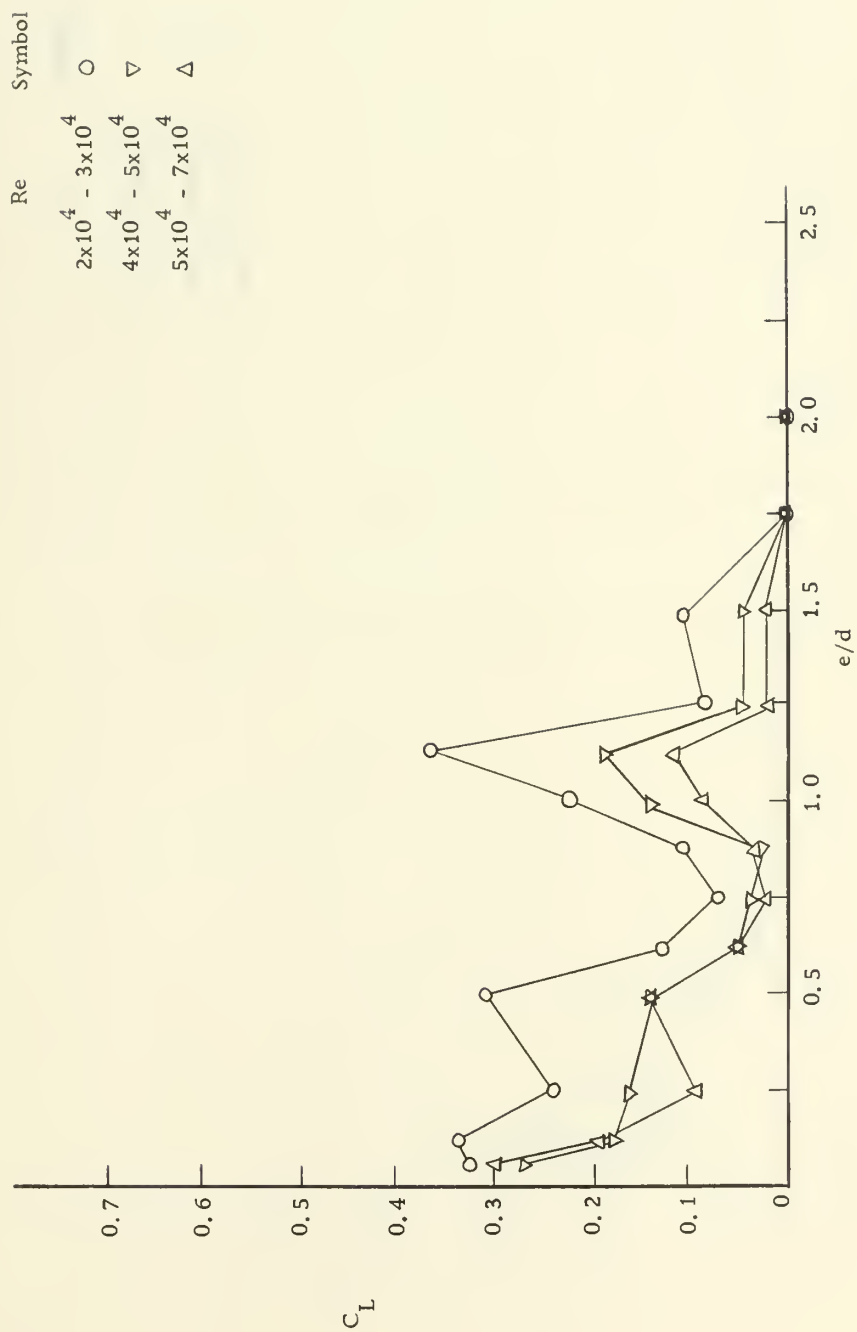


Figure 39. Hydrogen Bubble Visualization of the Flow Around a 5.1 cm Diameter Smooth Cylinder, $e/d = 2.0$.

Figure 40. Lift Force Coefficient for a Smooth Cylinder as a Function of e/d .

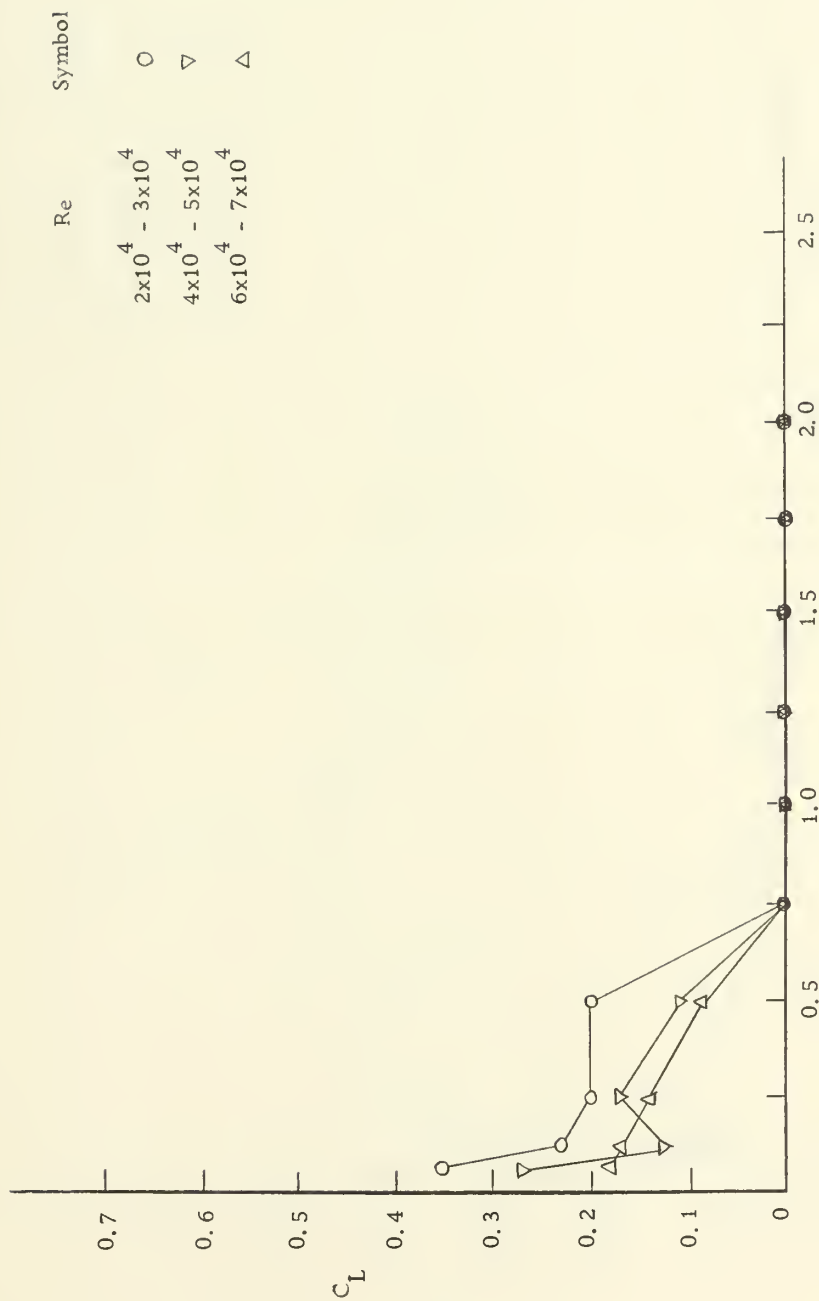


Figure 41. Lift Force Coefficient for Roughened Cylinder, as a Function of e/d , $0.0165 < e/d < 0.0234$.

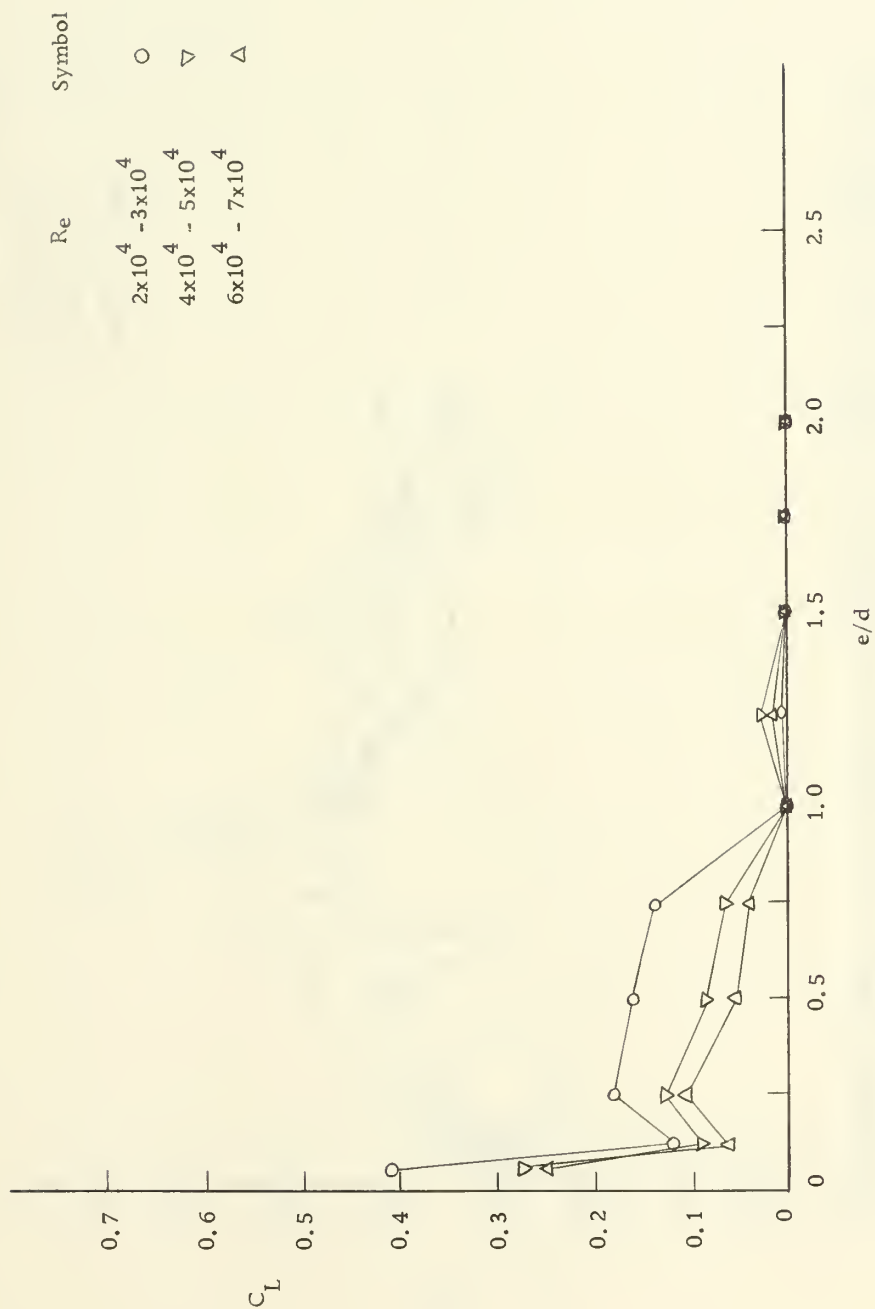


Figure 42. Lift Force Coefficient for a Roughened Cylinder as a Function of e/d , $0.0325 < \epsilon/d < 0.0468$.

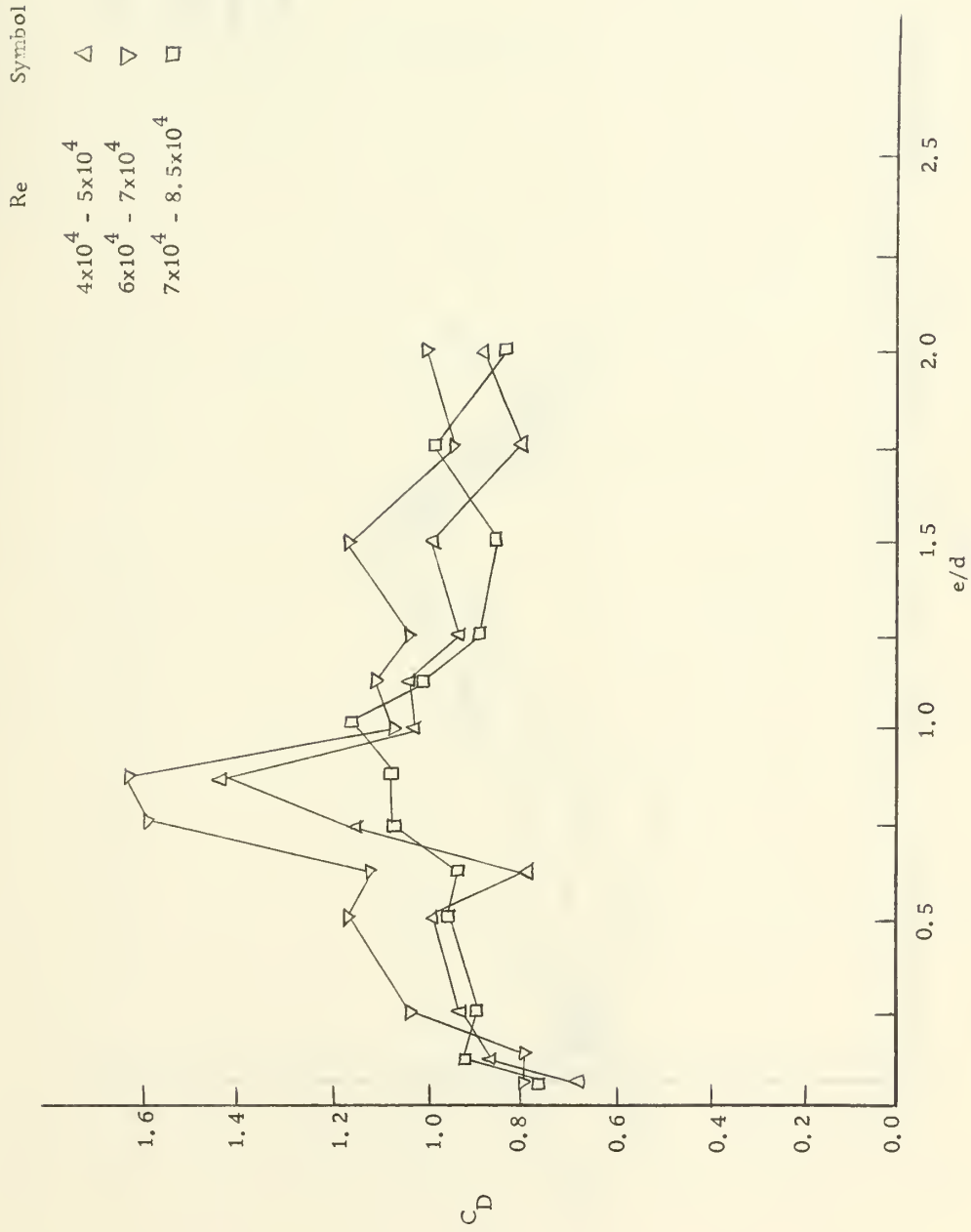


Figure 43. Drag Force Coefficient for a Smooth Cylinder as a Function of e/d .

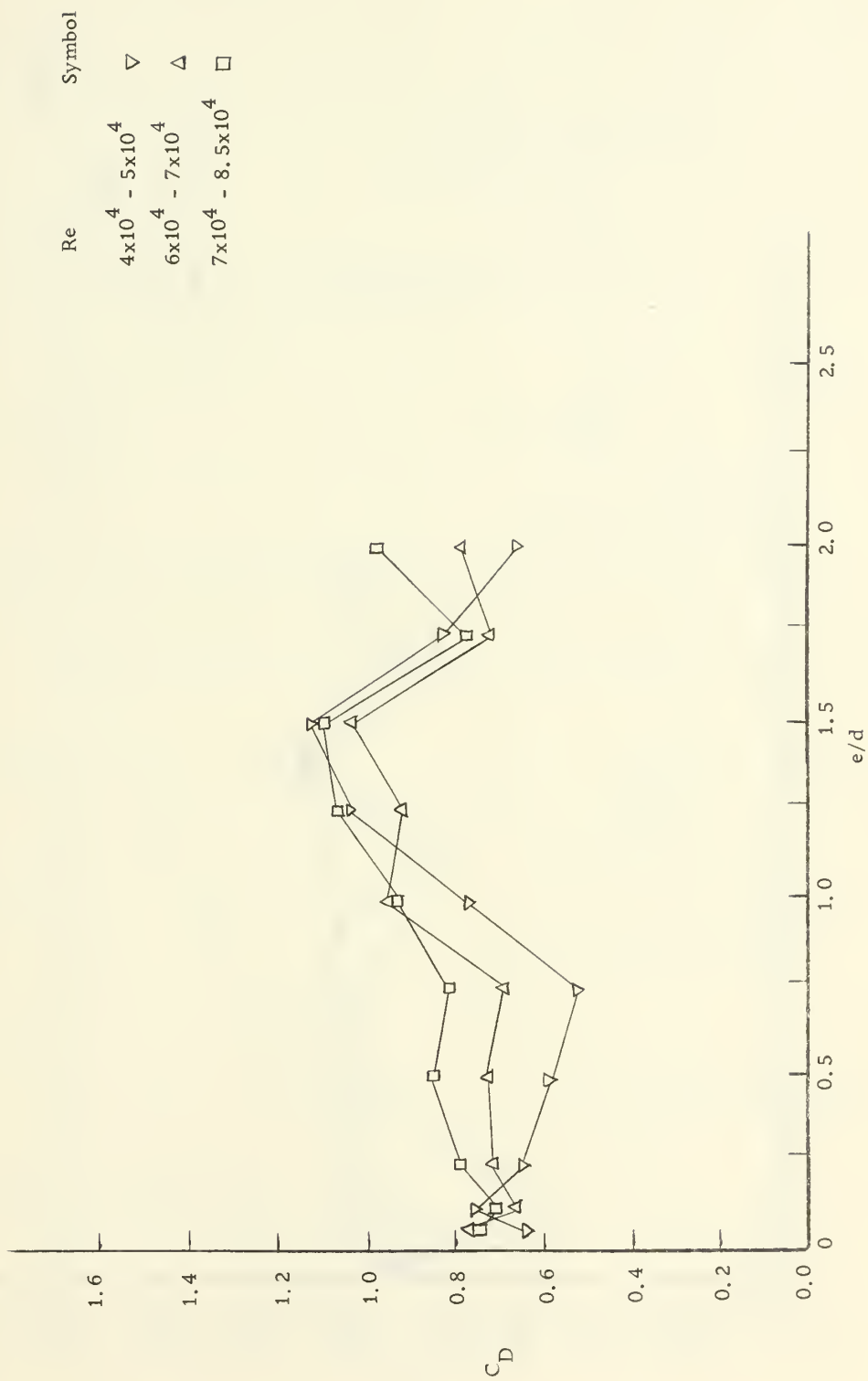


Figure 44. Drag Force Coefficient for Roughened Cylinder as a Function of e/d , $0.0165 < e/d < 0.0234$.

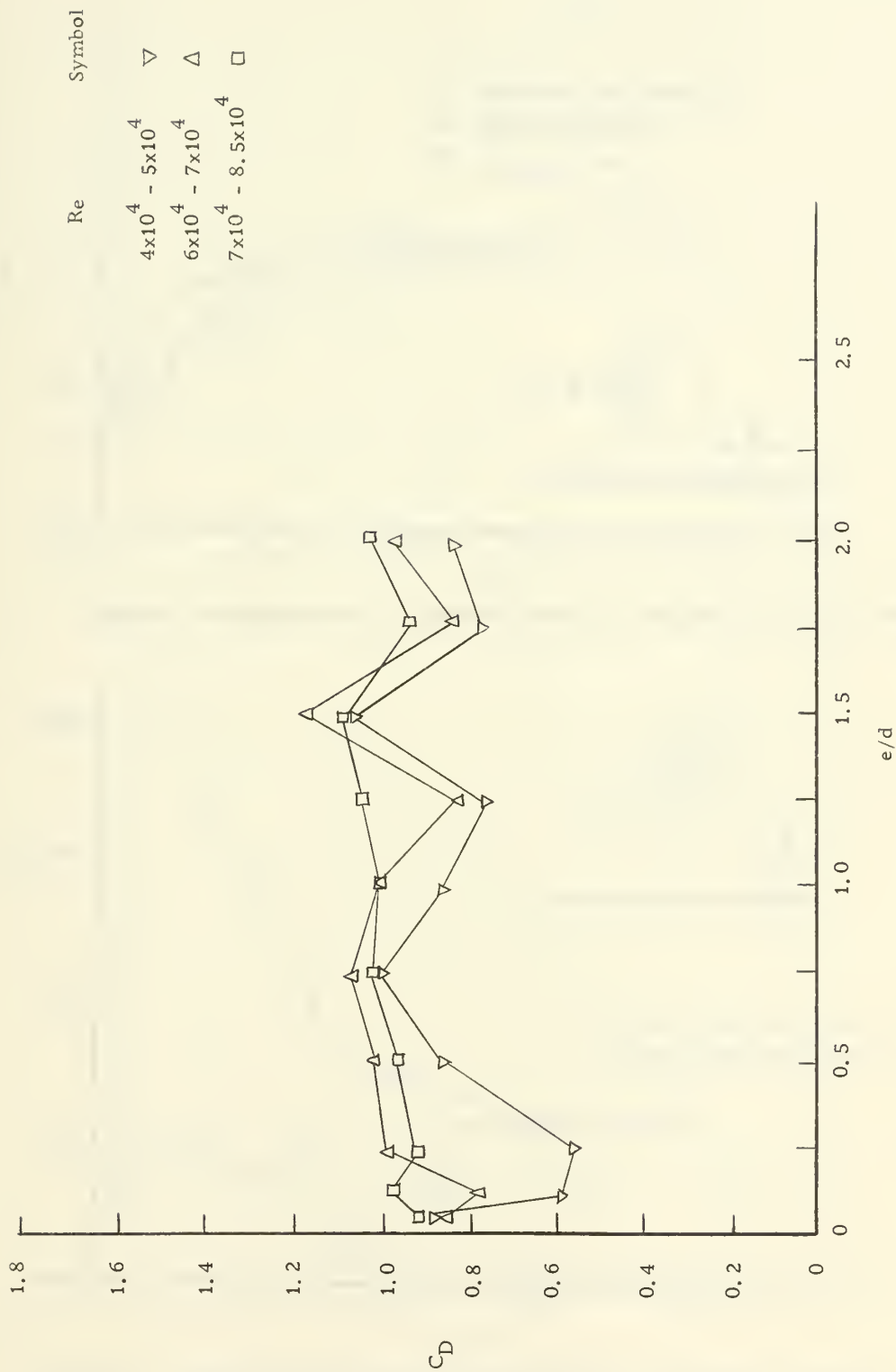


Figure 45. Drag Force Coefficient for Roughened Cylinder as a Function of e/d , $0.0325 < \epsilon/d < 0.0468$.

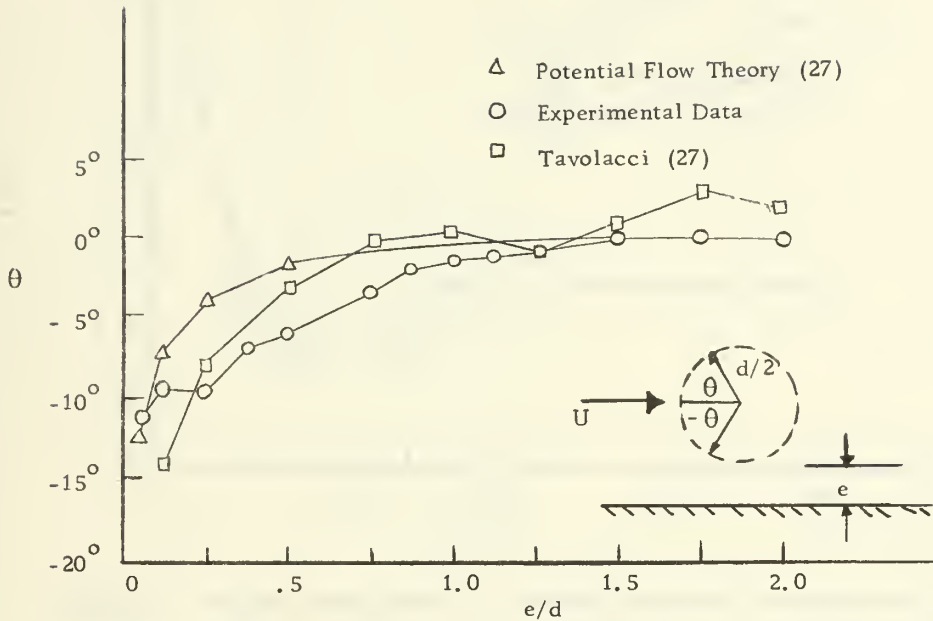


Figure 46. Stagnation Point on a Smooth Cylinder as a Function of e/d , $Re = 5800$.

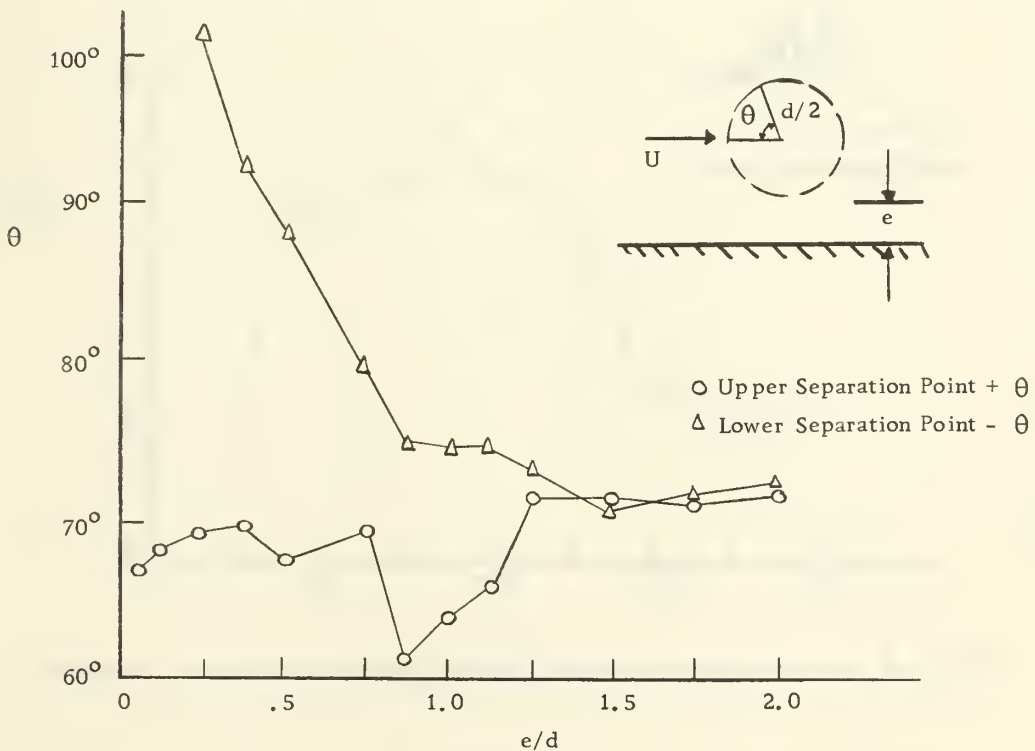


Figure 47. Upper and Lower Relative Separation Points on a Smooth Cylinder as a Function of e/d , $Re = 5800$.

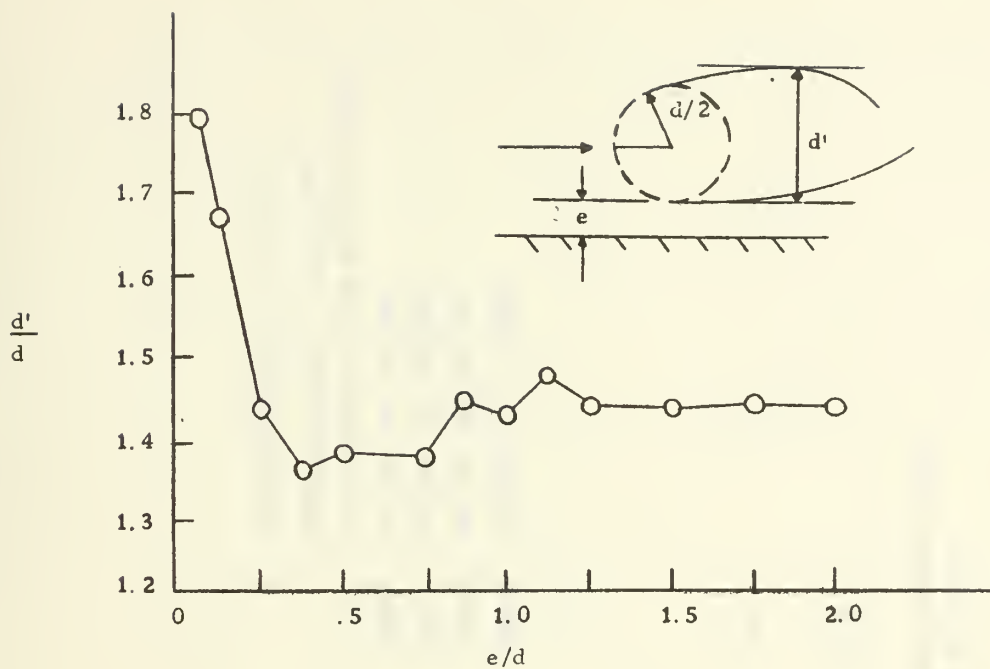


Figure 48. Relative Wake Width for a Smooth Cylinder as a Function of e/d , $Re = 5800$.

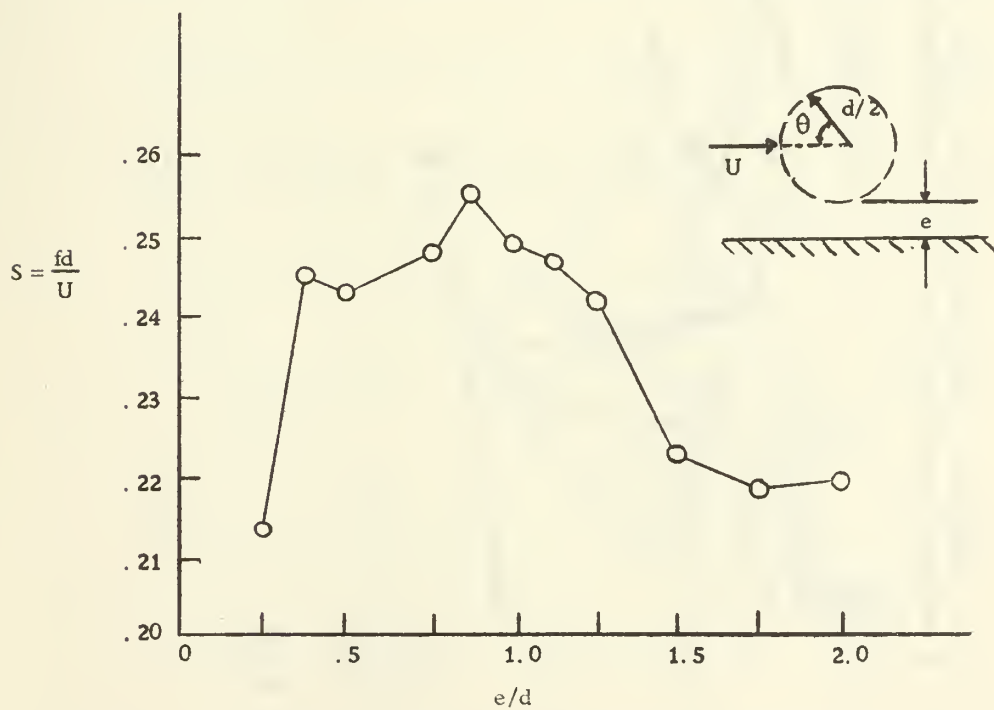


Figure 49. Strouhal Number for a Smooth Cylinder as a Function of e/d , $Re = 5800$.

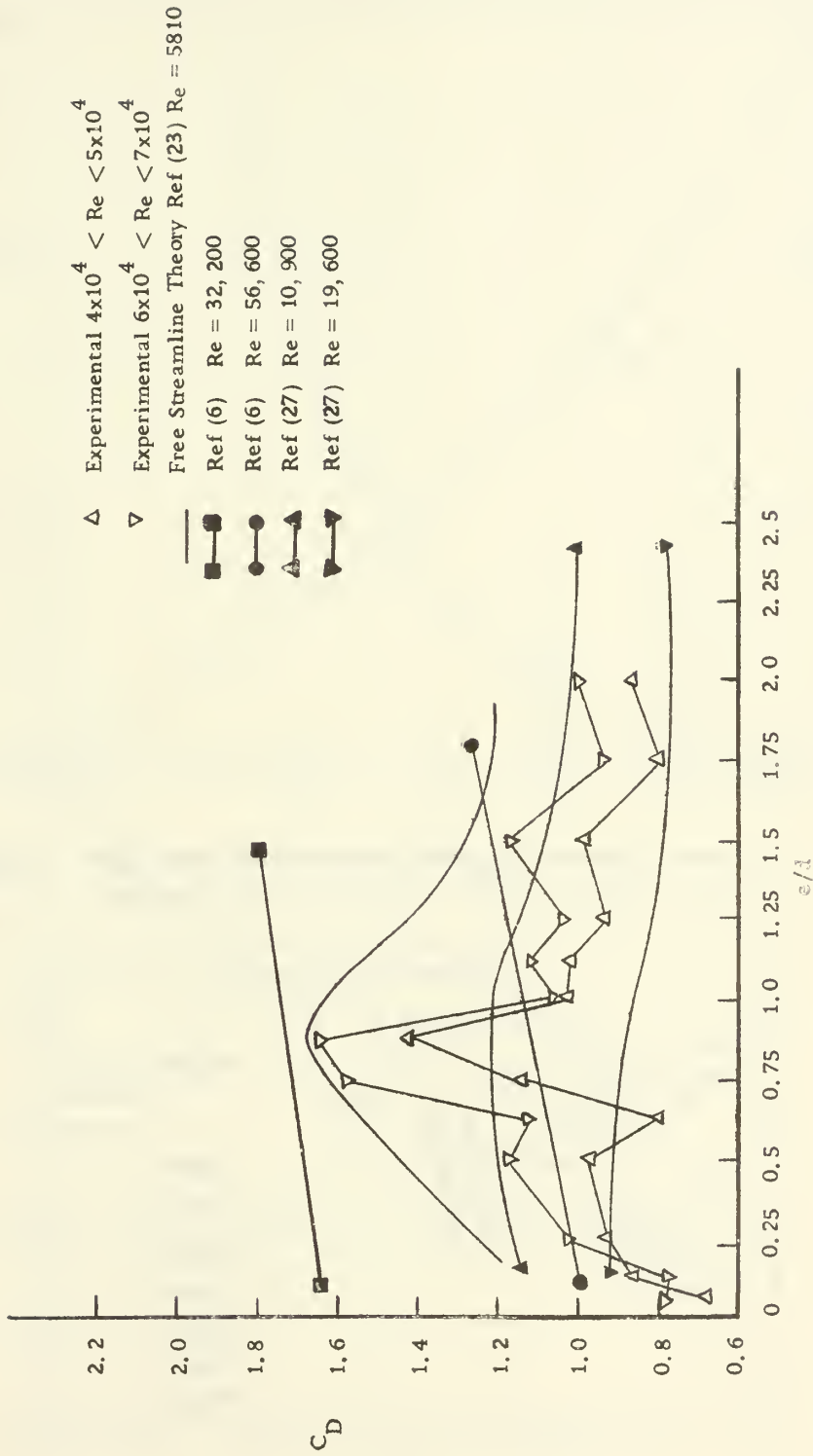


Figure 50. Comparison of Drag Force Coefficients for a Smooth Cylinder as a Function of e/d .

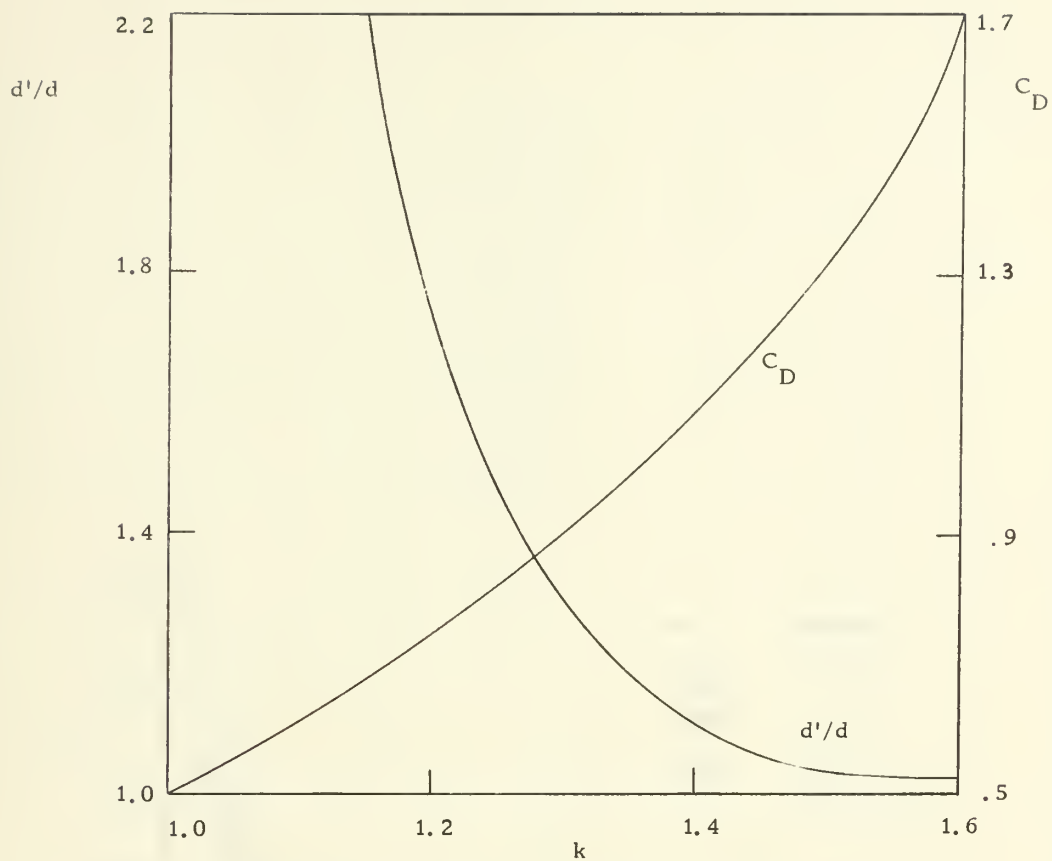


Figure 51. Wake Width and Coefficient of Drag for a Smooth Cylinder as a Function of the Base Pressure Parameter, k , (23).

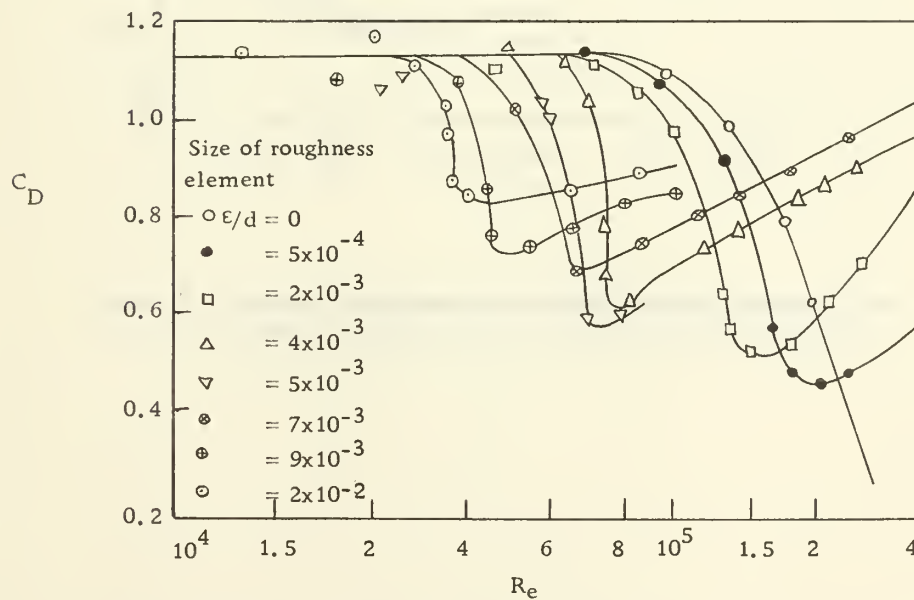


Figure 52. Drag Force Coefficient on Circular Cylinders at Varying Surface Roughnesses, (24).

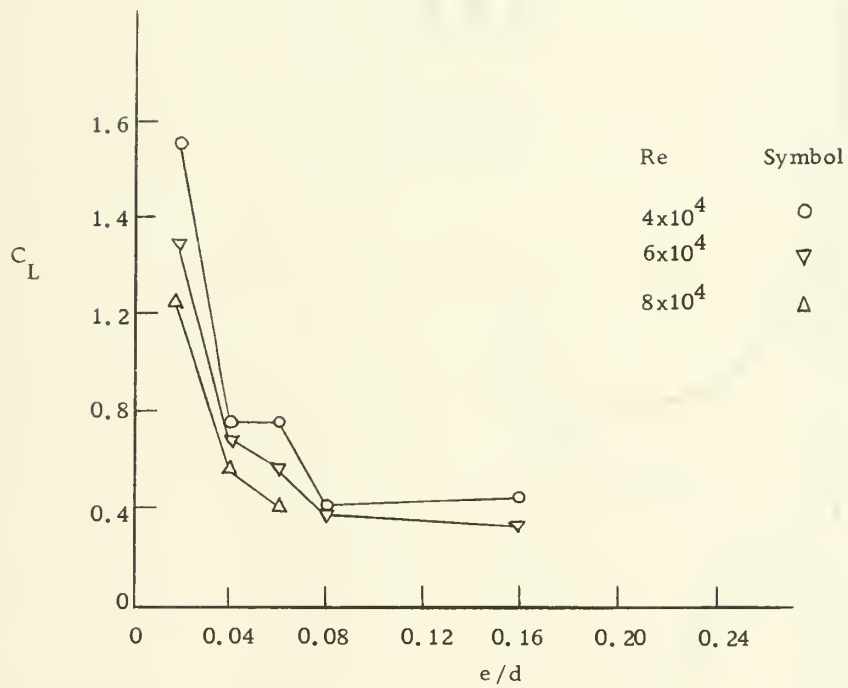


Figure 53. Lift Force Coefficient on a Smooth Cylinder Immersed in the Boundary Layer as a Function of e/d ($e+d/\delta \approx 0.55$), (12).

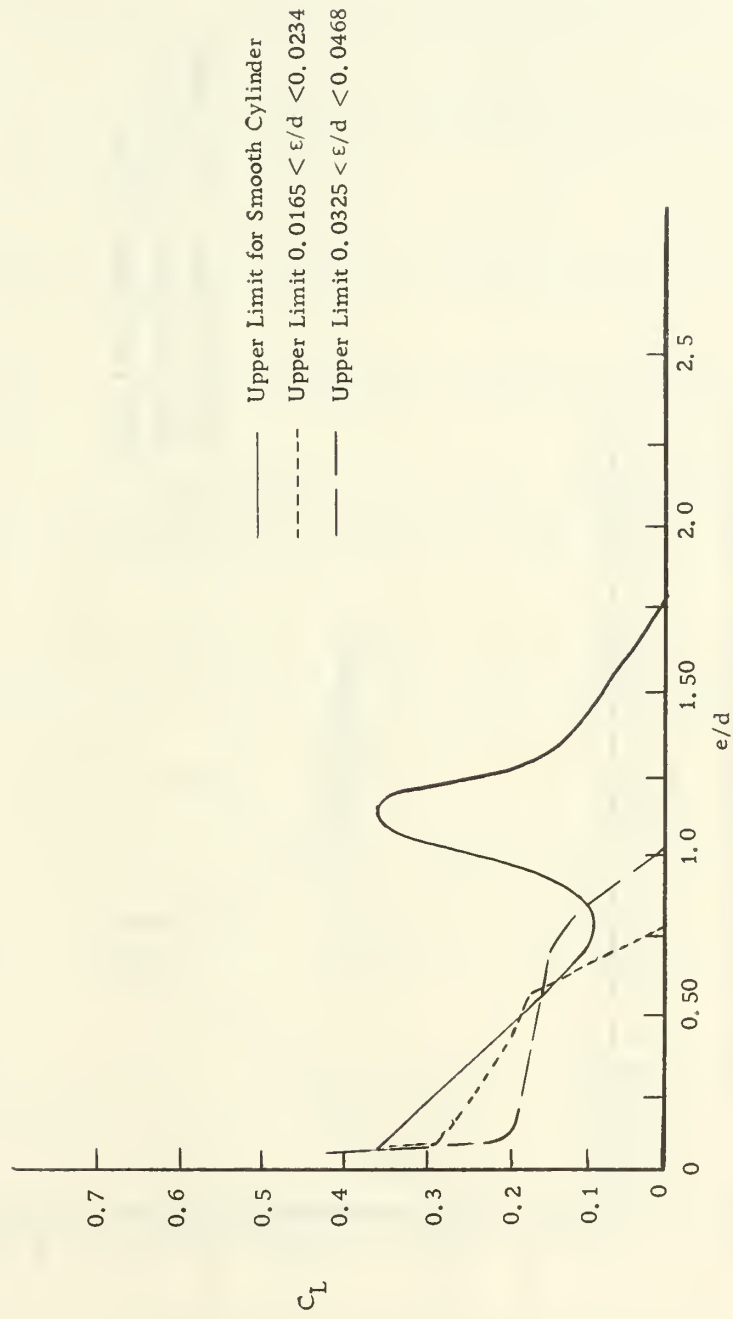


Figure 54. Maximum Values of Coefficient of Lift as a Function of e/d .

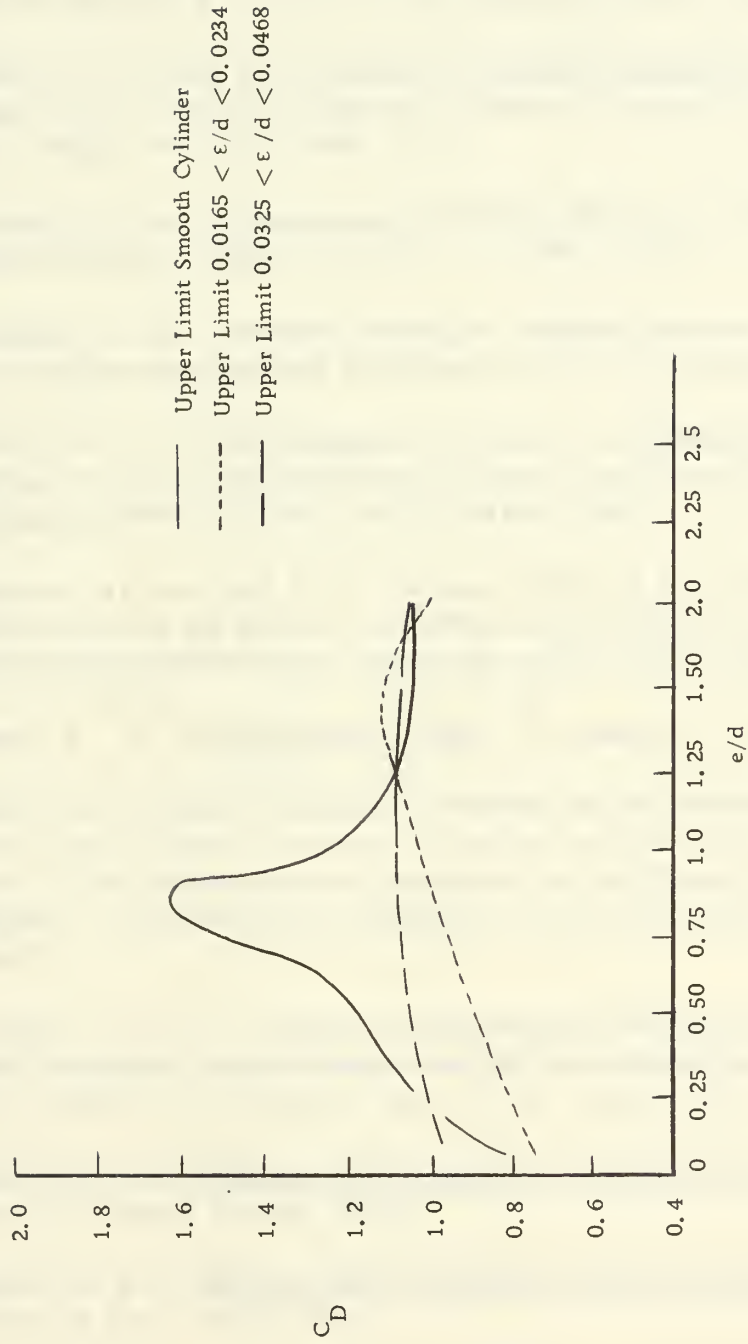


Figure 55. Maximum Values of the Coefficient of Drag as a Function of e/d .

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Tabular Results of Experimentation in the Wind Tunnel
and Water Channel

TABLE 1. Lift and Drag Data for a Smooth Circular Cylinder

e/d	Velocity (m/sec)	Re	Drag (newtons)	Lift (newtons)	C _D	C _L
0.0625	3.93	25,322	--	0.18	--	0.33
0.0625	7.61	48,942	1.60	0.55	0.78	0.27
0.0625	11.30	72,665	3.01	1.33	0.68	0.30
0.0625	13.06	83,993	4.56	--	0.76	--
0.125	3.93	25,322	--	0.19	--	0.34
0.125	7.11	45,736	1.39	0.33	0.78	0.18
0.125	10.33	66,468	3.29	0.70	0.87	0.19
0.125	12.96	83,352	5.48	--	0.92	--
0.25	3.93	25,322	--	0.14	--	0.26
0.25	6.54	42,103	1.58	0.24	1.03	0.12
0.25	9.83	56,850	3.16	0.31	0.93	0.09
0.25	13.29	85,489	5.63	--	0.90	--
0.50	3.93	25,322	--	0.18	--	0.32
0.50	7.34	47,232	2.25	0.27	1.17	0.14
0.50	10.43	67,109	3.77	0.55	0.98	0.14
0.50	12.96	83,352	5.73	--	0.96	--
0.625	3.93	25,322	--	0.08	--	0.13
0.625	7.04	45,309	1.75	0.08	1.12	0.05
0.625	11.63	74,803	3.56	0.22	0.79	0.05
0.625	12.96	83,352	5.40	--	0.94	--
0.75	3.93	25,322	--	0.04	--	0.07
0.75	7.31	47,019	3.03	0.05	1.59	0.03
0.75	10.30	66,254	4.37	0.08	1.15	0.02
0.75	13.39	86,130	6.87	--	1.08	--
0.875	3.93	25,322	--	0.06	--	0.11
0.875	7.24	46,592	3.07	0.05	1.64	0.02
0.875	9.91	63,903	5.06	0.10	1.44	0.03
0.875	12.86	82,711	6.87	--	1.08	--

TABLE I. (Continued)

e/d	Velocity (m/sec)	R_e	Drag (newtons)	Lift (newtons)	C_D	C_L
1.0	3.91	23,322	--	0.13	--	0.23
1.0	7.38	47,443	2.03	0.26	1.05	0.15
1.0	10.37	66,681	3.99	0.34	1.04	0.09
1.0	13.89	89,336	8.01	--	1.16	--
1.125	3.91	25,322	--	0.20	--	0.37
1.125	7.41	47,660	2.17	0.38	1.11	0.19
1.125	10.30	66,254	3.90	0.45	1.03	0.12
1.125	13.29	85,489	5.41	--	1.02	--
1.25	3.91	25,322	--	0.04	--	0.08
1.25	7.51	48,301	2.09	0.08	1.04	0.04
1.25	11.20	72,790	4.19	0.08	0.94	0.02
1.25	12.96	83,352	5.34	--	0.89	--
1.50	3.91	25,322	--	0.06	--	0.11
1.50	6.84	44,027	1.47	0.06	1.17	0.04
1.50	10.20	65,613	3.19	0.06	0.99	0.02
1.50	12.92	83,138	4.66	--	0.86	--
1.75	3.90	25,322	--	0	--	0.0
1.75	7.41	47,660	1.85	0	0.94	0.0
1.75	10.60	68,178	3.23	0	0.80	0.0
1.75	13.52	86,985	6.41	--	0.98	--
2.0	3.90	25,322	--	0	--	0.0
2.0	7.28	46,805	1.92	0	1.01	0.0
2.0	10.50	67,536	3.47	0	0.88	0.0
2.0	13.49	86,771	5.31	--	0.81	--

TABLE II. Lift and Drag Data for Circular Cylinder, $0.0165 < \epsilon/d < 0.0234$

ϵ/d	Velocity (m/sec)	R_ϵ	Drag (newtons)	Lift (newtons)	C_D	C_L
0.0625	3.75	24,117	--	0.18	--	0.35
0.0625	7.15	46,019	1.18	0.49	0.64	0.27
0.0625	9.92	68,843	2.68	0.64	0.76	0.18
0.0625	12.30	79,137	4.07	--	0.75	--
0.125	3.78	24,333	--	0.12	--	0.23
0.125	7.19	46,274	1.39	0.22	0.75	0.12
0.125	10.02	64,470	2.38	0.62	0.66	0.17
0.125	12.19	78,411	3.76	--	0.71	--
0.25	3.68	23,666	--	0.10	--	0.20
0.25	7.23	46,509	1.22	0.31	0.65	0.17
0.25	9.99	64,294	2.57	0.49	0.72	0.14
0.25	12.96	83,352	4.71	--	0.79	--
0.50	3.68	23,666	--	0.10	--	0.20
0.50	7.27	46,764	1.11	0.20	0.59	0.10
0.50	10.38	66,803	2.30	0.36	0.73	0.09
0.50	12.43	79,830	4.68	--	0.85	--
0.75	3.68	23,666	--	0	--	0.0
0.75	7.14	45,901	0.96	0	0.53	0.0
0.75	9.95	64,019	2.45	0	0.69	0.0
0.75	11.65	74,921	3.89	--	0.81	--
1.0	3.64	23,431	--	0	--	0.0
1.0	7.14	45,901	1.27	0	0.77	0.0
1.0	9.99	64,294	3.38	0	0.95	0.0
1.0	11.70	75,235	4.56	--	0.94	--
1.25	3.68	23,666	--	0	--	0.0
1.25	6.90	44,392	1.77	0	1.04	0.0
1.25	10.13	65,176	3.33	0	0.91	0.0
1.25	11.56	74,392	5.00	--	1.05	--
1.50	3.64	23,431	--	0	--	0.0
1.50	7.34	47,235	2.16	0	1.12	0.0
1.50	9.98	64,196	3.68	0	1.04	0.0
1.50	12.53	80,627	6.18	--	1.10	--

TABLE II. (Continued)

e/d	Velocity (m/sec)	R_e	Drag (newtons)	Lift (newtons)	C_D	C_L
1.75	3.57	22,980	--	0	--	0.0
1.75	6.74	43,352	1.32	0	0.82	0.0
1.75	9.50	61,117	2.32	0	0.72	0.0
1.75	11.37	73,156	3.58	--	0.78	--
2.0	3.61	23,215	--	0	--	0.0
2.0	7.14	45,901	1.20	0	0.66	0.0
2.0	9.74	62,490	2.67	0	0.79	0.0
2.0	11.85	76,215	4.90	--	0.98	--

TABLE III. Drag and Lift Data for Circular Cylinder, $0.0325 < \epsilon/d < 0.0468$

e/d	Velocity (m/sec)	R_ϵ	Drag (newtons)	Lift (newtons)	C_D	C_L
0.0625	3.67	23,627	--	0.20	--	0.41
0.0625	7.08	45,568	1.57	0.49	0.87	0.27
0.0625	10.22	65,745	3.22	0.93	0.86	0.25
0.0625	13.24	85,156	5.56	--	0.89	--
0.125	3.60	23,176	--	0.05	--	0.11
0.125	6.99	44,941	1.01	0.16	0.58	0.09
0.125	9.87	64,176	2.70	0.23	0.77	0.06
0.125	12.61	81,117	5.53	--	0.97	--
0.25	3.71	23,862	--	0.09	--	0.18
0.25	7.15	45,980	1.03	0.22	0.56	0.12
0.25	10.22	65,725	3.68	0.41	0.99	0.11
0.25	12.48	80,274	5.05	--	0.91	--
0.50	3.71	21,862	--	0.08	--	0.16
0.50	7.26	46,725	1.62	0.16	0.86	0.08
0.50	9.85	63,352	3.53	0.17	1.01	0.05
0.50	12.82	82,450	5.61	--	0.96	--
0.75	3.68	23,647	--	0.07	--	0.14
0.75	7.09	65,607	1.79	0.12	1.00	0.06
0.75	10.52	67,686	4.25	0.17	1.07	0.04
0.75	12.08	77,686	5.34	--	1.02	--
1.0	3.64	23,411	--	0	--	0.0
1.0	7.09	45,607	1.52	0	0.85	0.0
1.0	10.08	64,843	3.62	0	1.0	0.0
1.0	12.35	79,431	5.43	--	1.0	--
1.25	3.82	24,549	--	0	--	0.0
1.25	6.85	44,078	1.29	0.03	0.77	0.02
1.25	10.05	64,588	2.97	0.05	0.82	0.01
1.25	11.98	77,098	5.36	--	1.04	--
1.50	3.82	24,549	--	0	--	0.0
1.50	6.89	44,352	1.81	0	1.07	0.0
1.50	10.35	66,588	4.48	0	1.17	0.0
1.50	12.35	79,431	5.93	--	1.08	--
1.75	3.64	23,392	--	0	--	0.0
1.75	7.00	45,058	1.02	0	0.78	0.0
1.75	10.58	68,039	3.37	0	0.84	0.0
1.75	12.28	79,000	4.90	--	0.91	--
2.0	3.67	23,627	--	0	--	0.0
2.0	7.22	46,431	1.57	0	0.84	0.0
2.0	10.18	65,490	3.65	0	0.98	0.0
2.0	12.66	81,470	5.95	--	1.03	--

TABLE IV. Flow Characteristic Data for a Smooth Circular Cylinder (Averaged)

e/d	Stagnation (degrees)	Separation (degree)		d'/d	$S = \frac{fd}{U}$
		Upper	Lower		
0.0625	-11.3	66.5	--	1.78	--
0.125	-9.1	67.7	--	1.66	--
0.25	-9.7	68.9	-99.7	1.43	0.213
0.375	-6.8	69.3	-91.4	1.35	0.244
0.50	-6.0	67.0	-87.2	1.37	0.242
0.75	-3.1	69.0	-79.1	1.37	0.247
0.875	-1.9	61.2	-74.2	1.44	0.254
1.00	-1.6	63.7	-74.1	1.42	0.248
1.125	-1.1	65.6	-74.4	1.47	0.246
1.25	- .6	71.2	-72.9	1.43	0.241
1.50	0	70.8	-70.5	1.43	0.222
1.75	0	70.8	-71.4	1.44	0.218
2.00	0	71.6	-71.9	1.45	0.219

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